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Neurocognitive Research in Post-Stroke Aphasia: Comparison of Linguistic and Nonlinguistic Cognitive Control Functions

THESES OF PHD DISSERTATION

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1. Introduction

Even though our knowledge of post-stroke aphasia is continuously growing, a comprehensive and unified model is still missing for an integrative explanation of the heterogeneity of the produced symptoms.

The theoretical framework of the current research is based on the cognitive control model (Cohen, 2017), which has a solid neurological foundation (Frontal–Cingular–Parietal network), and involves the executive function system (Niendam, et al., 2012). To manage complex tasks the cognitive control system is responsible for the synchronization of its processes such as working memory, attentional control or proactive interference control. It means that the cognitive control system directs the activations of representations in working memory, sustains these activations, and reduces interference in order to achieve goal-directed behavior.

The control of both behavior and language can be characterized as parts of a continuum of automatic and controlled processes (Cohen, Dunbar, & McClelland, 1990, Botvinick & Cohen, 2014; Code, 2005). First, behavioral control processes, in a particular task, can be determined along a continuum from automatic to fully controlled. In general, the less control is required by a task, the more likely the behavior relies on automatic processes. In contrast, the more complex a task, the more control is needed for appropriate performance; in this case, behavior relies more on cognitive control processes. The magnitude and complexity of control depends on whether a conflict or interference is present in the actual task or whether additional attentional resources are needed (Kane, Conway, Hambrick, & Engle, 2008; Cohen, 2017). Second, similarly to the cognitive control model, language performance can also be evaluated along a continuum of control. Along this continuum, language performance depends on the accessibility of language control functions, language modalities and processes of language levels (Code, 2005).

Post-stroke aphasia is traditionally viewed as an acquired language impairment, due to a focal brain lesion (American Speech-Language-Hearing Association, 2020; Bánréti, 2014; Osmánné, 1994). It means that language disturbances may involve a various degree of the impairment in language production, language processing, as well as in language control (Haarmann, Davelaar, & Usher, 2003; Kolk, 1999). A person with aphasia has often relatively intact nonlinguistic cognitive skills, such as memory and executive function (American Speech-Language-Hearing Association, 2020).

In some studies, transcortical motor aphasia (TMA) is treated as a type of nonfluent aphasia, (Kertesz, 1979), whereas others consider this dysfunction as an executive function disorder

(Ardila, 2010). Based on these observations, dissociative relations might be assumed among individuals with Broca's aphasia and TMA on the basis of their linguistic and nonlinguistic abilities (Ardila, 2010; Bánréti, 2014). In case of similar linguistic and nonlinguistic profiles in cognitive control functions, these two nonfluent groups of aphasia would only differ in severity (Buckingham, 1999). This result would support the view that in severe aphasia both domain-general and linguistic control functions are impaired, while in individuals with mild aphasia both their behavior and communication are better supported by their language and cognitive control functions (Code, 2005; Buckingham, 1999).

Contrary to this, during the last decades, there has been mounting evidence that individuals with aphasia also demonstrate nonlinguistic processing deficits (Kasselimis, 2015), which might contribute to their language deficits (Nozari & Novick, 2017; Purdy, 2002; Kuzmina & Weekes, 2017). There might be a number of nonlinguistic impairments behind the linguistic symptoms that can be associated with different language processes and elements (Kuzmina & Weekes, 2017; Novick, Trueswell, & Thompson-Shill, 2005; Nozari & Schwartz, 2012; Ye & Zhou, 2009). As noted before, cognitive control is a complex mental system which is responsible for the execution of goal-directed behavior according to the changing environment (Diamond, 2013; Cohen, 2017). It is unclear whether language performance is supported by more domain general (Nozari & Schwartz, 2012) or domain specific functions (Hula & McNeil, 2008) .

Our next assumption is based on both research evidence and clinical experience, namely that the stroke itself might result in a slowing of cognitive operations, which might be independent from the aphasia-specific slowing (Alderman, 2016). Since aphasic symptoms often derive from a stroke, the resulting slowing in information processing might be the cumulative result of stroke-specific and aphasia-specific slowing, which can be detected in both linguistic and nonlinguistic domains (Yoo, 2017).

In sum, there is no clear evidence of the role of domain-general cognitive dysfunctions in language performance deficits (American Speech-Language-Hearing Association, 2020; McNeil, Hula, & Sung, 2011; Nozari & Schwartz, 2012). Moreover, it is not clear whether cognitive control deficits are specific to the linguistic domain in post-stroke aphasia (Hula & McNeil, 2008) or extend to the nonlinguistic domain too (Rodd, Johnsrude, & Davis, 2010). Finally, there are only a few results about the effects of stroke in information processing (Su, Wuang, Lin, & Su, 2015) and it is not clear whether slow processing speed in people with aphasia is specific to this population exhibiting language disorders, or originates from the stroke itself.

2. Purpose of the Research

The goal of the present study was to test the impact of differential cognitive control deficits on language performance in individuals with different types of nonfluent aphasia by comparing performances of individuals with post-stroke aphasia and control groups in specific tasks of information processing. Cognitive control tasks included vigilance, selective attention, response inhibition task, as well as linguistic and nonlinguistic working memory tasks which examined resistance to distractor and to proactive interference and memory updating processes. Performance profiles in these specific cognitive control functions reveal a complex picture about the underlying mental mechanisms of post-stroke nonfluent aphasia.

Hypothesis:

1) There are differences between the performances of individuals with Broca's aphasia and TMA in both nonlinguistic (domain-general) and linguistic (domain-specific) cognitive control functions (Schumacher, Halai, & Lambon Ralph, 2019; Kuzmina & Weekes, 2017; Murray, 1999). Participants with Broca's aphasia demonstrate lower performance in domain-specific cognitive control tasks than participants with TMA. However, we hypothesize the opposite profile in domain-general control functions (Jefferies & Lambon Ralph, 2006; Hula & McNeil, 2008).
2) There are differences between the performances of individuals with both Broca's aphasia and TMA in domain-general cognitive control tasks compared to the stroke and the control groups (Kasselimis, 2015).
3) Individuals in the stroke group demonstrate lower performance in domain-general cognitive control tasks than individuals in the control group, however there is no difference between these groups in linguistic cognitive control functions (Alderman, 2016; Yoo, 2017).

3. Methods

3.1. Participants

Twenty-two participants with aphasia (PWA) – 9 with Broca's aphasia, and 13 with TMA – were recruited from the National Medical Rehabilitation Center (Budapest). One of the control groups comprised 13 participants who had had an ischemic stroke attack, but demonstrated no language disorder. They were participants of the same institute as PWA. The second control group included 13 healthy, age-matched control participants who had no aphasia and no history of stroke, traumatic brain injury or other neurological or psychiatric illness (1. Table).

Demographic and Diagnostic values/Groups	Broca's aphasia	TMA	Stroke	Control
SEX (M/F)	6/3	8/5	2/10	7/6
AGE N(SD)	52,11 (7,62)	56,83 (9,38)	60,36 (7,58)	51,85 (8,38)
YEARS OF EDUCATION N(SD)	12,89 (2,37)	14,23 (3,55)	12,92 (3,37)	13,08 (1,64)
WAB SUBTESTS:				
Information content	2,63*	5,18		
Fluency	2,5*	3,82		
Comprehension	6,21.	7,58		
Naming	1,75*	4,58		
Repetition	2,00**	8,36		
AQ – (WAB)	30,06**	59,23		
TOKEN	9,38.	17,80		
BOSTON	9,25.	20,1		

1. Table. Demographic and Diagnostic data of experimental groups. The performance of individuals with Broca's and TMA were compared with Mann-Whitney U test.

3.2. Procedures and Methods

All participants were presented with 2 computer-based tasks which were the Attention tasks, the Complex Recalling Paradigm (CRP), which had a linguistic and a nonlinguistic version with exactly the same structure and item types but different stimuli. All tasks were presented using E-Prime software. Participants were seated in front of a laptop computer and were asked to respond to stimuli that appeared on the computer screen.

Generally, 4 experimental sessions were taken, each of the sessions lasted 1, 1,5 hours. The schedule of the sessions was adjusted to special needs and fatigue of participants, so during the experiment we took breaks in every 45 minutes. The experiment lasted approximately 3 weeks with individuals with aphasia, and 1 or 1,5 weeks with control groups.

3.2.1. Attention Tasks

This measurement included three subtasks: (i) vigilance task, (ii) distractor interference task, and (iii) motor response inhibition task.

The first subtask measured participant's *vigilance* ability. Vigilance means sustaining one's attention in a long-lasting task resolution. Participants were asked to respond to the stimulus that appeared on the computer screen by pushing the appropriate button. If the stimulus - which was a simple dot - appeared on the right side of the computer, they had to push the right button, however, if the dot appeared on the left side of the computer screen, they needed to push the left button.

The *distractor interference* task examined the orientation of attention, and the ignorance of distractor stimuli. A distractor stimulus with different color was added to the paradigm. In this task two dots (a target and a distractor) appeared on the screen at the same time in each trial. Participants needed to ignore the distractor stimuli.

In the *motor response inhibition* task selective attention and motor response inhibition abilities were measured. Participants were asked to respond to the target by pressing the response button and to the distractor by withholding this automatic response and pressing the start button. Thus, individuals needed to suppress their automatic motor response and press a different button.

3.2.2. Complex Recalling Paradigm (CRP)

The non-verbal CRP task measured individual’s attention, recollection and updating of working memory, and proactive interference control. It included two subtasks and used abstract figures that are difficult to name as stimuli: (1) Baseline task, and (2) Cue task.

(1) We used the Baseline task as a reference to the Cue task. The baseline task included two item types: true target and new distractor stimulus. Participants were asked whether an individual item appeared in the set of three stimuli that was introduced in the previous probe.

(2) In the Cue task we used the same item types as in the baseline task, however, a *cue* was presented after the stimuli. The role of the *cue*, which was checkerboard, was to direct individual’s attention to the position of the target item in the original stimuli set. Participants were asked whether the item (target or distractor) had an identical position in the stimulus set to the position of the *cue*.

The paradigm included five item manipulations; however, only three were included in this research. Beyond the previously introduced two types of stimuli (true target and new distractor), interference stimuli supplemented the stimulus set.

- true target: the function of these stimuli was to measure attention and working memory storage. Participants needed to maintain the activation of the target stimuli to make a decision about the probe, and the correct response was to accept the true target stimuli.
- new distractor: the function of these stimuli was to measure attention and working memory recollection based on newness and familiarity. Participants needed to make a decision based on familiarity, and the correct response was to reject new distractors.
- interference item: to be able to respond correctly to an interfering item it is important to recognize the difference between relevant and irrelevant stimuli and to ignore irrelevant ones.

3.2.3. Linguistic tasks

In addition to condition and stimulus manipulation in the CRP task, the types of the stimuli were manipulated as well. The items in the linguistic CRP task were prototypical pictures (Rossion & Pourtois, 2004). The words collected were high frequency (1000-10000), everyday nouns composed of two syllables in Hungarian.

Pictures represent linguistic representations through their semantic content and they are useful in facilitating semantic processing (Bohnemeye, 2014). Images as representational referents elicit language mechanisms, unlike abstract figures. Thus, images as stimuli are convenient to measure manipulations on linguistic representations. The structure, number of trials, item types (target, distractor, interference) did not differ between the linguistic and nonlinguistic tasks.

3.3. Data analysis

We used *linear mixed effects modeling* for data analysis, which represents the sensitivity of the variables to specific effects, and establishes those effects which have the greatest influence on variable alignment. The small sample size and not normal distribution of data, as well as the complexity of the data justified the use of linear modeling. In this study only reaction time data were analyzed.

R program was used to build models when new effects were added to the model. The best fitting candidates were chosen for analysis, and models were compared using ANOVA. Results were considered significant if $p < .05$. In the CRP task the Cue/Baseline ratio was calculated, which provided information about the performance in the Cue task compared to the Baseline task. If the *Cue/Baseline* ratio was less than 1, participants probably applied the *cue* to generate strong binding between the item and its position. It follows, that *Cue/Baseline < 1* value can be interpreted as the signal of strong binding in working memory. If the *Cue/Baseline* ratio was more than 1, participants probably did not demonstrate strong binding between the item and it's position, so the *Cue/Baseline > 1* value can be the signal of weak binding in working memory.

Since we had only two types of stimulus manipulations in the baseline task, we had to use the average of the median of log-transformed reaction time data of the target and the median of log-transformed distractor stimuli for each individual in the Baseline task. This was called ($logRt\_Baseline_{contracted}$). Later all the data in the Cue task were divided by this $logRt\_Baseline_{contracted}$ for each individual.

$$logRt\_ratio_i = \frac{logRt\_Cue_{stimuli,i}}{logRt\_Baseline_{contracted}}.$$

4. Main results

4.1. Nonlinguistic cognitive control

4.1.1. Attention task

In vigilance, distractor interference and response inhibition tasks individuals with Broca's aphasia and TMA did not differ, however both groups with PWA demonstrated slower responses both than the group of individuals with stroke and individuals in the control group (2. Table). There was no difference between individuals with stroke and the control group in response time measures.

	Broca's	**TMA**	**Stroke**	**Control**
Broca's	-			**
TMA		-	.	**
Stroke	*	.	-	
Control	**	**		-

2. Table. Attention tasks. Reaction Time differences between groups.
*Significance code: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

4.1.2. CRP task

Individuals with Broca's aphasia demonstrated slower responses than individuals with TMA, stroke and control participants. There were no other group differences in this task (3. Table).

	Broca's	**TMA**	**Stroke**	**Control**
Broca's	-	**	**	***
TMA	**	-		
Stroke	**		-	
Control	***			-

3. Table. Nonlinguistic CRP task. Reaction time differences between groups.
*Significance code: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

4.2. Linguistic cognitive control

4.2.1. CRP task

Individuals with Broca aphasia demonstrated slower responses than individuals with TMA, stroke, and individuals in the control group (4. Table). Participants with TMA provided slower responses to items than control group, however there was no difference between the groups of individuals with TMA and stroke in response time measures.

	Broca's	TMA	Stroke	Control
Broca's	-	*	***	***
TMA	*	-		.
Stroke	***		-	
Control	***	.		-

4. Table. Linguistic CRP task. Reaction time differeneces between groups.

5. Discussion

This section has the following structure. (1) Comparison of performances between the groups of individuals with Broca's aphasia and TMA; (2) Comparison of performances between the groups of nonfluent aphasia with the group of individuals with a stroke and the neurotypical control participants; (3) Comparison between the groups with individuals with a stroke and the neurotypical controls.

5.1. Nonlinguistic cognitive control

5.1.1. Comparison of performances between the groups of individuals with Broca's aphasia and TMA

In this section we present together the interpretation of results in the attention and the CRP tasks. Results in both *attention task and CRP task* contradicted our hypothesis that stated that individuals with TMA would demonstrate weaker performances in these domain-general cognitive control functions including vigilance, selective attention, working memory updating, conflict resolution and proactive interference control compared to the group of individuals with Broca's aphasia, based on Ardila's definition of TMA (Ardila, 2010). Instead of this profile, individuals with Broca's aphasia demonstrated slower responses than individuals with TMA.

The assumed impairment of cognitive control functions in TMA cannot be observed neither in attention nor in working memory updating or proactive interference control compared to Broca's aphasia. It can be inferred that the accessibility of these cognitive control functions might correspond to the severity of aphasia (Marinelli, Spaccavento, Craca, Marangolo, & Angelelli, 2017), so we assume that the symptoms of severe Broca's aphasia are aligned with more severely impaired subfunctions of cognitive control compared to TMA.

This result is in agreement with previous studies, where severe aphasia symptoms were related to the impairment of more subfunctions of cognitive control, like short-term memory, or working memory (Potagas, Kasselimis, & Evdokimidis, 2011). Taking into account that in these studies authors did not differentiate nonfluent aphasias (they focused on AQ), our research might supplement these results with the idea that mobilizing working memory processes can be slower in only severe nonfluent aphasia.

The continuity hypothesis of language performance (Buckingham, 1999; Code, 1989; Code, 2018) can help us to explain this result. The difference between performances in Broca's and TMA groups depends on the impairment of language modalities and domain-general cognitive control functions. The more severe the aphasia, the more domain-general cognitive control function is damaged (Potagas, Kasselimis, & Evdokimidis, 2011; Kuzmina & Weekes, 2017). In Broca's aphasia significant amounts of language and domain-general cognitive control functions are impaired compared to TMA. In contrast, there are fewer language deficits and fewer cognitive control dysfunctions in individuals with TMA. This leads to the assumption that a more flexible cognitive control system is available in people with TMA.

5.1.2. Comparison of performances among the groups of nonfluent aphasia, individuals with a stroke without aphasia, and the neurotypical control participants

We begin with the interpretation of the performance pattern of participants with Broca's aphasia. In both the *attention task* and the *CRP task* participants with Broca's aphasia showed slower response times compared to the stroke and the control groups.

The slower maintenance of attentional focus seems to be independent of the general slowing effect due to the stroke itself, based on the differences between reaction time of individuals with Broca's aphasia and the stroke group. The impairment of the orientation of attention together with the maintenance of stimulus representations might be responsible for a lower performance in attention tasks in severe nonfluent aphasia. We can infer that besides the language symptoms, the impairment of selective focused attention and the impairment of motor response resolution might be present in severe nonfluent aphasia. Our results are in accordance with the results of previous studies (Lee & Pyun, 2014; LaCroix, Tully, & Rogalsky, 2020, Ewans, 2014; Murray, 1999).

The higher response time of individuals with Broca's aphasia compared to the stroke and control groups in the *CRP task* can be established based on the model of cognitive control (Cohen, 2017). The results of pair-wised comparisons of reaction times in the proactive interference condition between the participants with Broca's aphasia and the individuals with stroke and the neurotypical control participants suggest that resistance to proactive interference is impaired in Broca's aphasia. This deficit in proactive interference control may reflect that these individuals maintain the activation of working memory representations longer than needed, even when those representations are already irrelevant, therefore show a delayed and/or weaker activation of the relevant representations (Oberauer, 2002; Oberauer, Süß, Wilhelm, & Sander, 2008). The working memory capacity is limited by resistance to proactive interference (Pettigrew & Martin, 2016; Wilhelm, Hildebrandt, & Oberauer, 2013). Participants with Broca's aphasia, demonstrated slowness in short term maintenance of working memory representations, which might be one of the consequences of the impairment of resistance to proactive interference. We found impaired resistance to proactive interference in our previous research in group of individuals with heterogenous aphasia types. Our current results supplement this finding in the group of Broca's aphasia.

Additionally, we also found evidence for the impairment of suppressing simultaneously activated representations. The weak resistance to this type of interference can be explained by weak binding between items and their physical position (Beaman, 2004). The weak binding is indicated by the *Cue/Baseline* ratio, which was less than 1 in the groups of TMA, stroke and controls. This implies that they correctly applied the *cue*, which helped them to maintain the bindings between items and their positions. This was not observed in individuals with Broca's aphasia, in fact the *Cue/Baseline* ratio was more than 1.

The proper application of the *cue* strengthens the binding between the stimulus and its position, thereby stronger representations might develop, which decrease both the interference effect and the possibility of forgetting (Oberauer, Süß, Wilhelm, & Sander, 2008). Individuals with Broca's aphasia could not benefit from the *cue*, which indicates weak binding between the stimuli and the context. Weak binding does not allow appropriate resistance to interference (Oberauer, 2002), which is responsible for the appearance of weak memory traces. An intense interference effect appeared, because representations that should have been suppressed due to task demands, still had high activation levels. The dual mechanism of suppression of irrelevant representations and the increase of activation of relevant representations seems to be impaired in individuals with Broca's aphasia, which directly leads to further limitations in working memory capacity.

We conclude, that it is possible that weaker resistance to interference results in weakness of working memory processes and attentional capacity (Meier & Kane, 2017; Hasher, Lustig, & Zacks, 2007). However, it should be added that these dysfunctions interact with weak language functions as well, as attested in the current study by the performance of participants with Broca's aphasia. This is in line with previous studies where authors established conflict resolution impairment in lexical access in this population (Nozari & Schwartz, 2012; Ye & Zhou, 2009). However, our results display new insights into the profile of cognitive control functions in post-stroke nonfluent aphasia, and prove that domain-general cognitive control functions are impaired in Broca's aphasia.

Individuals with TMA demonstrated slower response time compared to the stroke and control groups only in the *attention tasks*. This profile contradicts our hypothesis (we expected slower performance in the TMA group than that in the stroke group in all non-linguistic tasks). We can conclude, that in nonfluent aphasia there is a slowness in vigilance, in orientation of attention, as well as selective attention (Murray, 2012; LaCroix, Tully, & Rogalsky, 2020). As an explanation, slowness in orientation of attention and in selective attention might be responsible for slow decision-making processes (Kane, Bleckely, Conway, & Engle, 2001). The slow decision making might increase uncertainty in response selection of a task. This leads to unsuccessful ignorance or inhibition of irrelevant and distracting stimulus in nonfluent aphasia (Szöllősi, Lukács, & Zakariás, 2015).

Participants with TMA demonstrated similar performance in the *CRP task* to participants with stroke. The performance of individuals with TMA indicates that despite their attentional deficit, stroke-affected individuals with mild language disorder are able to mobilize their cognitive resources in ways similar to stroke affected participants with no language disorder. This result contradicts our hypothesis, because slower performance was expected in the TMA group compared to the stroke and the control groups. This pattern allows the interpretation that performance in the CRP task in individuals with TMA might be related to stroke-specific slowing rather than aphasia.

Their similar performance was only displayed in the complex working memory tasks, however, in the simple vigilance tasks they demonstrated poorer performance. Previous studies provided evidence of attentional deficits in aphasia, and found a correlation between attentional control functions and the severity of aphasia (Lee & Pyun, 2014). Our findings suggest that there is no difference between severe and mild nonfluent aphasia in attentional control, however, they significantly differ in managing working memory representations. Participants with TMA might mobilize cognitive resources more effectively, indicated by their similar performance to the stroke group, and higher performance than the Broca's group.

Mild language disorder is accompanied by flexible cognitive capacity, which is manifested in effective maintenance and manipulation of representations. Previous studies implied that the improvement of language functions is correlated with the improvement of general cognitive abilities, which proves the interrelation between language and attention, cognitive control functions, and working memory (Seniów, Litwin, & Lesniak, 2009, Kang, Jeong, Moon, Lee, & Lee, 2016).

5.1.3. Comparison between the groups of individuals with a stroke and their neurotypical peers

In both the *attention task* and the *CRP task* the group of individuals with stroke showed similar reaction times to the control group. Despite of previous observations about the slowing effect of vascular stroke in information processing (Alderman, 2016; Su, Wuang, Lin, & Su, 2015), which can influence the adequate mobilization of cognitive control functions, in the current study this slowing did not appear to contribute neither to simple attentional functions, nor to working memory updating and proactive interference control. Previous papers have described psychomotor slowing due to stroke without aphasia (Su, Wuang, Lin, & Su, 2015), although there was no difference between these groups in simple attentional tasks.

Even though we only focused on the reaction time results in this study, we must note that participants with stroke demonstrated lower accuracy compared to the control group. Based on the accuracy differences it is likely that the well-documented psychomotor slowing in individuals with stroke is related to complex decision-making processes of attentional control and to the maintenance of response representations (Yoo, 2017). The results may also reflect a trade-off between speed of processing and accuracy.

Our results indicate that stroke influences the response selection and decision-making processes of the stimuli based on their familiarity and newness. An analysis of stimulus content, which requires the maintenance of the activation of representations for access to that content, should precede decision making. An inefficient maintenance of activation of representations might result in less accurate performance compared to the control group. Although when a task demands complex processes (conflict resolution, or proactive interference control), stroke-affected participants are able to activate and flexibly mobilize proper cognitive resources in time, in order to compensate for their limited short-term memory functions.

5.2. Linguistic cognitive control

5.2.1. Comparison of performances between the groups of individuals with Broca's aphasia and TMA

Participants with Broca's aphasia demonstrated slower responses than individuals with TMA in the linguistic *CRP task*. This suggests that the slowness that we have observed in nonlinguistic working memory updating, conflict resolution, and proactive interference in Broca's aphasia may be present in the linguistic domain as well (Kuzmina & Weekes, 2017). Presumably, linguistic control functions are not selectively impaired in Broca's aphasia, or in TMA. It is more likely that participants with Broca's aphasia -with a severe language disorder-show a more severe deficit in domain-general cognitive control than individuals with TMA. The control of language functions is at least in part connected to domain-general cognitive control, as shown by previous studies (Nozari, Swartz, 2011; Kuzmina, 2017; Christensen, Wright, & Ratiu, 2018; Rodd, Johnsrude, & Davis, 2010). Thus, high language performance is likely to be associated with intact general cognitive control, and higher cognitive flexibility.

To summarize, the dysfunction of domain-general cognitive control has been demonstrated in all types of nonfluent aphasia in previous research (Kuzmina & Weekes, 2017). According to these findings, overlapping linguistic and nonlinguistic control processes were emphasized, however, the authors did not differentiate between types of nonfluent aphasia. The current research supports the separate nature of control functions in nonfluent aphasias. For participants with severe aphasia, it is more difficult to mobilize cognitive control functions for goal achievement. While in mild aphasia, cognitive mechanisms which are activated in response to verbal and nonverbal stimuli, interact with each other, while in in Broca's aphasia the cognitive control system seems to be more fragmented.

5.2.2. Comparison of performances among the groups of nonfluent aphasia, individuals with a stroke without aphasia, and the neurotypical control participants

In this section we begin our discussion with the performance of individuals with Broca's aphasia compared to performance of individuals with stroke and control group in the *CRP task*. In line with our predictions, linguistic control functions in Broca's aphasia were slower compared to those of individuals with stroke and the control group.

The results can be explained based on the cognitive control model (Cohen, 2017). Slower responses of individuals with Broca's aphasia compared to the stroke and control groups seems to stem from impaired interference control. This impairment in participants with Broca's aphasia might be related to their difficulties in decision making with regards to the relevance of the stimuli and to suppressing irrelevant representations (Nozari & Schwartz, 2012; Piai, Roelofs, Acheson, & Takashima, 2013). These individuals demonstrate difficulties in shifting their attention level from one representation to the other in order to produce a correct response. Decreased activation of representations leads to weak memory traces; as a result, participants forget the information easier (Engle, 2018; Oberauer, Süß, Wilhelm, & Sander, 2008). Our findings are aligned with previous results that emphasize cognitive control deficits in nonfluent aphasia (Ivanova, Dragoy, Kuptsova, Ulicheva, & Laurinavichyute, 2015)

Similar to their performance in resistance to proactive interference in the nonlinguistic tasks, the *Cue/Baseline* ratio was more than 1 in the group of individuals with Broca's aphasia in linguistic task as well. It is possible that, the binding of linguistic stimuli to the context is impaired which is reflected in the incorrect use of the *cue*. This might be associated with a low activation of representations and together with poor binding, resistance to interference is diminished or slowed down. The same pattern was observed in the nonlinguistic tasks. We can conclude that cognitive operations of resisting interference are slow in both linguistic and nonlinguistic tasks in Broca's aphasia. This impairment blocks the production of increased linguistic memory traces, which may result in slow decision-making in Broca's aphasia. Overall, domain-general cognitive control functions seem to be impaired in Broca's aphasia (Schumacher, Halai, & Lambon Ralph, 2019; Kuzmina & Weekes, 2017; Murray, 1999).

Participants without aphasia demonstrated normal general attentional control and proactive interference control functions. Moreover, the lexical-semantic information might facilitate coding processes of representations in these groups. A combination of these factors leads to an effective supervisory mechanism. Although lexical-semantic information probably helps to manipulate representations in working memory in Broca's aphasia, due to severe impairment in domain-general cognitive control functions, this facilitation is not sufficient to decrease the group differences in the CRP tasks.

Our results of participants with TMA demonstrated similar reaction times to the stroke group. However, they displayed slower responses compared to the neurotypical control group.

Most deficits in individuals with TMA can be explained by the effect of the stroke which is indicated by the results that suggest no difference in reaction time between the stroke and the TMA groups in most tasks. Instead of the impact of aphasia, which is mild in this group, a stroke-specific deficit contributes to their weaker attentional and linguistic cognitive control. The stroke-specific slowing related to the impairment of maintaining working memory activations, might influence participants' slower performance compared to the control group.

Goal oriented behavior is supervised at higher levels (Meier & Kane, 2017; Diamond, 2013), which in healthy individuals is composed of strongly interacting mechanisms. Accessing linguistic information is a well-organized process which can be impeded due to severe dysfunction of the cognitive system, which affects the success of communication (Purdy, 2002; Ye & Zhou, 2009), however, different cognitive resources are more accessible for participants with mild than with more severe language disorders.

5.2.3. Comparison between the groups of individuals with a stroke and their neurotypical peers

There was no difference in the reaction time data in the *CRP task* between the stroke and the control groups in the language control functions. In other words, in the stroke group the speed of processing that is involved in managing the activation of representations based on familiarity and newness seems to be intact. The above-mentioned stroke-specific slowing did not affect the response times of participants who had no aphasia.

We do not present accuracy data in this study, however we found accuracy differences in performance between individuals with stroke and the control group, similar to the nonlinguistic tasks. We mention this accuracy result for the same reason as in nonlinguistic tasks, because based on the reaction time data one might misinterpret the performance of individuals with stroke, as they demonstrate no difference in speed of processing compared to the controls.

However, accuracy data imply that the process of comparison between the representations based on familiarity and newness seems to be impaired. This dysfunction indicates that participants often choose rejection incorrectly instead of acceptance of the targets, or they accept distractor stimuli instead of rejecting them. Again, there is a tradeoff between accuracy and speed of processing in the stroke group.

These results fit the cognitive control model if we consider stroke-specific slowing (Yoo, 2017) as a delay in sustained activation of representation for the access of mental processes (Cohen, 2017). We suppose that psychomotor slowing, which is a well-documented symptom after a stroke (Alderman, 2016), is related to the deficit of keeping representations active in short-term memory. This process might be delayed, which promotes impaired decision-making processes (Kane, et al., 2004). This stroke-specific domain-general short-term memory dysfunctions influence cognitive processes in aphasia as well. However, it is important to note that in severe language disorders aphasia-specific dysfunctions even in domain-general cognitive control functions (working memory updating, conflict resolution, and proactive interference control) are present as well. This cumulated effect of stroke-specific and aphasia-specific dysfunctions can be responsible for the poor performance of individuals in Broca's aphasia in all tasks compared to the control group.

6. Limitations

The generalization of the results has some limitations because of the relatively small sample sizes and the heterogeneity of participants in the stroke group.

The reason for small sample sizes is that we followed strict inclusion criteria in recruiting participants. This was needed to allow us to answer the research questions of this study. We selected members of groups according to language profiles, while finding the suitable participants with Broca's and TMA aphasia created major difficulties. In addition to the language criteria compliance and contra-indication criteria needed to be considered (e.g., neglect syndrome, internal medical status), which caused a further decrease in the possible number of participants involved.

Another limitation can be the composition of the stroke group. We involved participants with both right and left hemisphere stroke. Early in our research we planned to recruit individuals with dominant (left) hemisphere stroke without language disorder, however, we found only a very low number of participants. As a compromised solution we extended the criteria of the stroke group and we involved participants who demonstrated stroke in their right hemisphere as well. Individuals in the stroke group were identical in their preserved language abilities. Participants with right hemisphere stroke had use their dominant hand for button press, whereas all other participants (those with left hemisphere stroke, participants with aphasia, and the neurotypical control group) used their non-dominant hand. Although the results of our pilot study found no difference in the most important conditions between the performances of individuals with left and right hemisphere stroke, we need to identify this pattern as a limitation.

It can be identified as a further scientific limitation that, despite the data cleaning, variables typically did not show a normal distribution, which was probably the result of leaving the salient values in the patterns. We considered it important to keep the heterogeneity of the performances of the different aphasia groups, and show a more natural picture of their behavior. Thus, leaving these values in the dataset, the number of suitable statistical probes decreased, and mostly non-parametric or regressive and correlation probes were used. To overcome this limitation, we also used hierarchical linear modeling, because this method is less sensitive to the sample size.

7. Conclusion

Current research focused on the involvement of linguistic and domain-general cognitive control functions in post-stroke nonfluent aphasias. We measured these functions in two groups of nonfluent aphasias and compared them to stroke- affected participants without aphasia, and a neurotypical control group.

In concordance with previous studies (Ewans, 2014; LaCroix, Tully, & Rogalsky, 2020), our findings indicate that attentional control functions are impaired in nonfluent aphasia. This impairment is independent on the negative effects of stroke, and of the severity of aphasia. This conclusion is proved by the result, i.e., significantly poorer performance in both Broca's and

TMA aphasia compared to the stroke group, and the equal performance in the groups of aphasias. Cognitive control seems to be impaired differently depending on the effect of stroke and the severity of aphasia. In addition to the influence of stroke, impairments in cognitive control are also present in aphasia (Potagas, Kasselimis, & Evdokimidis, 2011), hence it is important to conclude that language performance is affected by cognitive control functions.

Maintenance and orientation of attention are crucial in the process of generating and later keeping the appropriate activation of representations in working memory (Kane, Conway, Hambrick, & Engle, 2008). Slow attentional control functions can be associated with slow working memory, which is responsible for the management of activation of representations (Stedron, Sahni, & Munakata, 2005), although this relationship is typical in individuals with Broca's aphasia only. The delayed activation process results in more representations being active at the same time, which leads to a conflict between these simultaneously activated representations. The inhibition of irrelevant representations requires cognitive control functions (Botvinick, Carter, Braver, Barch, & Cohen, 2001; Cohen, Botvinick, & Carter, 2000).

We found impaired interference control in both linguistic and nonlinguistic domains, which leads us to conclude that domain-general cognitive control deficits are present in Broca's aphasia. As a result of this deficit both the suppression of irrelevant representations and the shifting to the following relevant stimuli become diminished or delayed (Oberauer, Süß, Wilhelm, & Sander, 2008). The deficit in interference control might contribute to the limited working memory capacity in Broca's aphasia. Overall domain-general cognitive control dysfunctions are parallel to severe language disorders in Broca's aphasia, which makes the updating and manipulation of working memory representations slow or impaired (Kuzmina & Weekes, 2017).

Our results support the interrelation between language performance and the cognitive control system (Buckingham, 1999; Code, 2018). This interaction between the language system and cognitive control system was supported by their neural organization in previous studies. The distributive neural activation pattern of language system shares neural regions with cognitive domains (Hickok & Poeppel, 2007, Blumstein & Amso, 2013). The similar neural correlates (Left Inferior Frontal Gyrus, Anterior Cingular Cortex) of these mental systems determine the overlaps in functional organization as well.

Nonfluent aphasias can be distinguished by both the characteristics of individual's language disturbances and, as our findings suggest, by the functions of domain-general cognitive control. Since we found differences in profiles in both the linguistic and nonlinguistic abilities of individuals with Broca's aphasia and TMA, we can conclude that these aphasia types differ from each other in the severity of cognitive and language functions (Buckingham, 1999). Individuals with TMA show slow attentional control functions, which possibly prevent the selection and activation of representations in working memory, although the results indicate relatively intact linguistic and nonlinguistic working memory storage, conflict resolution and proactive interference control processes.

In sum, the results show that the continuum of language control and behavioral cognitive control processes (Code, 1989; Code, 2005, Kane, Conway, Hambrick, & Engle, 2008; Cohen, 2017) determine parallel linguistic and nonlinguistic abilities. The severity of aphasia interacts with the severity of cognitive control dysfunctions (Buckingham, 1999; Code, 1989). This means that the better the language abilities, the more effective the cognitive control functions.

Contrary to our prediction, the existence of selective language control behind aphasia (Hula & McNeil, 2008; Jefferies, Hoffman, Jones, & Lambon Ralph, 2008; Hula, McNeil, & Sung, 2007) was not proved in this research. The language symptoms of post-stroke nonfluent aphasia interact with attentional control disorders (Kuzmina &Weekes, 2017; Murray, 2012), short-term memory dysfunctions (Potagas, Kasselimis, & Evdokimidis, 2011), dysfunctions of monitoring and updating processes in working memory (Nozari & Novick, 2017) and impairment of proactive interference control (Novick, Trueswell, & Thompson-Shill, 2005), although only in severe aphasia. In mild aphasia, such as in TMA, attentional control interacts with language symptoms. Other discrepancies compared with neurotypical groups potentially originate from stroke-specific slowing.

Our goal was to investigate the question of whether the impairment of cognitive control functions in post-stroke aphasia is independent from the effect of stroke, as well as what general influence stroke itself has on the cognitive control system.

Based on our results, stroke has an independent effect on information processing, especially on maintaining the activation of representations. This weakness might be interpreted as psychomotor slowing in previous studies (Alderman, 2016). This deficit can be detected differently in the performance of individuals with nonfluent aphasia (Yoo, 2017). The larger number of group differences indicates that in Broca’s aphasia, which represents a severe language disorder, stroke-specific and aphasia-specific slowness and impairments are jointly responsible for the poor performance in cognitive tasks.

In contrast to this, in TMA, which represents a mild language disorder, stroke-specific slowing seems to result in similar symptoms to those of stroke affected participants without aphasia, based on their similar performance in most cognitive control tasks. We assume that aphasia-specific slowing does not have a significant effect on the performance of individuals with TMA due to their mild language disorder, and their relatively intact cognitive control sub-functions, which jointly result in similar performance compared to neurotypical participants in many cognitive tasks.

To sum up: a better definition of aphasia is a cognitive disorder with prominent linguistic deficits rather than a language-specific disturbance (Kuzmina, 2017).

8. Clinical Relevance

In international practice, there are growing number of nonlinguistic therapies which, besides verbal reconstructive techniques (Seniów, Litwin, & Lesniak, 2009), focus on the improvement of cognitive functions as well. Despite the fact that in clinical practice more and more emphasis is being placed on evidence-based therapies, in Hungary there are still too few clinical methods dedicated to systematic investigations.

The results of the present research show that therapeutic success in the improvement of communication abilities of post-stroke aphasia can increase significantly if we take into account cognitive control functions, including proactive interference, attentional control and working memory processes. For example, n-back training, which targets working memory updating could be an efficient method to improve these domain-general cognitive abilities. Previous research has shown that as a result of n-back training, general language scores of participants with aphasia improved (Zakariás, Keresztes, Marton, & Wartenburger, 2018).

Other effective methods would be the computer-based cognitive control tasks, which are traditionally used as experimental tasks; however, their usefulness can be experienced as training tasks as well. To improve attentional control functions training with attentional tasks would be a useful, in addition to traditional language therapies (Helm-Estabrooks, 2002; Zhou, Lu , Zhang, Sun, & Li, 2018).

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[45]ADATLAP

a doktori értekezés nyilvánosságra hozatalához

I. A doktori értekezés adatai

A szerző neve: Szöllősi Izabella
MTMT-azonosító: 10046179
A doktori értekezés címe és alcíme: A post-stroke afázia neurokognitív vizsgálata: Nyelvi és nem nyelvi kognitív kontroll funkciók összehasonlítása.
DOI-azonosító[46]: DOI: 10.15476/ELTE.2021.029
A doktori iskola neve: Neveléstudományi Doktori Iskola
A doktori iskolán belüli doktori program neve: Gyógypedagógia Program
A témavezető neve és tudományos fokozata: Marton Klára, Ph.D, Habilitáció
A témavezető munkahelye: ELTE-BGGYK-GYMRI; ELTE-PPK-NTDI Gyógypedagógia Program; City University of New York

II. Nyilatkozatok

1. A doktori értekezés szerzőjeként[47]
a) hozzájárulok, hogy a doktori fokozat megszerzését követően a doktori értekezésem és a tézisek nyilvánosságra kerüljenek az ELTE Digitális Intézményi Tudástárban. Felhatalmazom a *Neveléstudományi Doktori Iskola* hivatalának ügyintézőjét *Barna Ildikót*, hogy az értekezést és a téziseket feltöltse az ELTE Digitális Intézményi Tudástárba, és ennek során kitöltse a feltöltéshez szükséges nyilatkozatokat.
b) kérem, hogy a mellékelt kérelemben részletezett szabadalmi, illetőleg oltalmi bejelentés közzétételéig a doktori értekezést ne bocsássák nyilvánosságra az Egyetemi Könyvtárban és az ELTE Digitális Intézményi Tudástárban;[48]
c) kérem, hogy a nemzetbiztonsági okból minősített adatot tartalmazó doktori értekezést a minősítés (*dátum*)-ig tartó időtartama alatt ne bocsássák nyilvánosságra az Egyetemi Könyvtárban és az ELTE Digitális Intézményi Tudástárban;[49]
d) kérem, hogy a mű kiadására vonatkozó mellékelt kiadó szerződésre tekintettel a doktori értekezést a könyv megjelenéséig ne bocsássák nyilvánosságra az Egyetemi Könyvtárban, és az ELTE Digitális Intézményi Tudástárban csak a könyv bibliográfiai adatait tegyék közzé. Ha a könyv a fokozatszerzést követőn egy évig nem jelenik meg, hozzájárulok, hogy a doktori értekezésem és a tézisek nyilvánosságra kerüljenek az Egyetemi Könyvtárban és az ELTE Digitális Intézményi Tudástárban.[50]
2. A doktori értekezés szerzőjeként kijelentem, hogy
a) az ELTE Digitális Intézményi Tudástárba feltöltendő doktori értekezés és a tézisek saját eredeti, önálló szellemi munkám és legjobb tudomásom szerint nem sértem vele senki szerzői jogait;
b) a doktori értekezés és a tézisek nyomtatott változatai és az elektronikus adathordozón benyújtott tartalmak (szöveg és ábrák) mindenben megegyeznek.
3. A doktori értekezés szerzőjeként hozzájárulok a doktori értekezés és a tézisek szövegének plágiumkereső adatbázisba helyezéséhez és plágiumellenőrző vizsgálatok lefuttatásához.

Kelt: Budapest, 2021.03.13.

a doktori értekezés szerzőjének aláírása

[45] Beiktatta az Egyetemi Doktori Szabályzat módosításáról szóló CXXXIX/2014. (VI. 30.) Szen. sz. határozat. Hatályos: 2014. VII.1. napjától.
[46] A kari hivatal ügyintézője tölti ki.
[47] A megfelelő szöveg aláhúzandó.
[48] A doktori értekezés benyújtásával egyidejűleg be kell adni a tudományági doktori tanácshoz a szabadalmi, illetőleg oltalmi bejelentést tanúsító okiratot és a nyilvánosságra hozatal elhalasztása iránti kérelmet.
[49] A doktori értekezés benyújtásával egyidejűleg be kell nyújtani a minősített adatra vonatkozó közokiratot.
[50] A doktori értekezés benyújtásával egyidejűleg be kell nyújtani a mű kiadásáról szóló kiadói szerződést.