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Cognitive processing load as a determinant of stuttering: Summary of a research programme

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Abstract
The present paper integrates the results of experimental studies in which cognitive differences between stuttering and nonstuttering adults were investigated. In a monitoring experiment it was found that persons who stutter encode semantic information more slowly than nonstuttering persons. In dual-task experiments the two groups were compared in overt word-repetition and sentence-production experiments. The results of the two word-repetition experiments indicate that the speech of stuttering persons is sensitive to interference from concurrent attention-demanding cognitive processing—particularly when phonological coding is involved. In two sentence-generation and -production experiments it was found that under dual-task conditions stuttering persons produced sentences containing a smaller number of content units whereas persons who do not stutter did not show a significant single- vs. dual-task contrast. These results suggest that sentence generation and production required greater sustained attentional processing in stuttering than in nonstuttering persons and that persons who stutter reduce the amount of "conceptual work" in order to keep their stuttering rates low. Data from an fMRI-study indicate that in persons who stutter the neural systems activated during sentence generation and production overlap to a greater extent than those of persons who do not stutter. It is suggested that in persons who stutter neural subsystems involved in speech planning are "modularized" to a lesser extent than in persons who do not stutter.

Keywords: *Stuttering, speech production, modularity, processing load, dual-task method*

Introduction

The present research programme essentially consists of a set of empirical results. In this introduction the theoretical background for these results will be presented. In order to focus this presentation on the points which are essential for the present approach, theories will be roughly subsumed under three general headings: speech motor control, speech plan decoordination, and demands and capacities.

Speech motor control theories of stuttering

This group of theories shares the assumption that stuttering is related to a deficiency in speech motor control. This deficiency has been conceptualized in widely differing ways.

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Smith and her collaborators (Smith, 1999; Kleinow & Smith, 2000; Smith & Kleinow, 2000) assume that stuttering events result from an inherent dynamic instability in the speech motor control system. Another variant of this group of theories assumes that persons who stutter use a motor control strategy that differs in several respects from that of persons who do not stutter: it relies to a greater extent on sensory feedback, the movements are performed less automatically, and the control strategy is characteristic of less highly developed speech motor systems (for summaries, see van Lieshout, 1995; Kent, 2000; Peters, Hulstijn, & van Lieshout, 2000). A third variant of this group of theories concentrates on the role of auditory feedback in stuttering (for an overview, see Howell, 2004a, b) or on the interplay between efferent and reafferent auditory control (Kalveram, 2000). Recently, anomalous gyral variants in the left and right perisylvian regions of adults with persistent developmental stuttering were found and have received considerable interest (Foundas, 2001; Foundas, Bollich, Corey, Hurley, & Heilman, 2001). However, in spite of their potential relevance for our understanding of stuttering, these latter results have not yet been replicated and the functional implications of the neuroanatomical differences are still a matter of speculation. One aim of the present research programme was to test whether deficiencies in the sensory-motor control system are necessary and sufficient to explain the development and maintenance of stuttering or whether additional factors related to cognitive processing of language must be taken into consideration. The monitoring experiment (see Table I), which will be presented in the following section, was designed to answer this question.

Desynchronization of the speech plan

The central assumption of this group of theories was most pithily formulated by Perkins, Kent, and Curlee (1991). In their view, speech involves linguistic and paralinguistic

Table I. Overview of the experimental paradigms used in the present research programme.

Monitoring Experiment		
Task:	A prespecified target word had to be monitored during silent reading	Bosshardt and Fransen, 1996
Monitoring Conditions:	Identical word, rhyme, category	Bosshardt and Fransen, 1996
Dual-Task Experiments		
Tasks:	Word-repetition and sentence-production tasks, which had to be performed concurrently with a second task	
Word-Repetition Experiments		
Speaking Task:	Participants were instructed to orally and continuously repeat a sequence of words	Bosshardt, 1999, 2002
Secondary Tasks:	Mental calculations	Bosshardt, 1999
	Silent reading and memorizing of words	Bosshardt, 2002
Sentence-Production Experiments		
Immediate Production:	Participants were instructed to produce a sentence containing two nouns as soon as the nouns were presented	Bosshardt, Ballmer and de Nil, 2002
Delayed-Production:	Participants were instructed to silently generate a sentence containing two nouns as soon as the nouns were presented and then to produce them overtly 10 sec later	de Nil and Bosshardt, 2000
Secondary Tasks:	Rhyme or category decisions	de Nil and Bosshardt, 2000; Bosshardt et al., 2002

components, each of which is processed by different neural systems that converge on a common output system. Fluent speech requires that these components be integrated in synchrony and stuttering can result when parts of the speech plan are incorrectly timed. In people who stutter, Sommer, Koch, Paulus, Weiller, and Büchel (2002) observed neuroantomical evidence for cortical disconnection immediately below the laryngeal and tongue representations in sensorimotor cortex. They conclude from their findings that persistent developmental stuttering results from disturbed timing of activation in speech-relevant brain areas. The results of Salmelin, Schnitzler, Schmitz, and Freund (2002) support this interpretation. On the basis of their behavioural and developmental observations of stuttering behaviour in different languages, Howell and Au-Yeung (2002; see also Howell, 2004a) more specifically proposed that stuttering results from defective interaction between linguistic planning and the execution of speech movements. In Howell's view, stuttering can arise when after production of previous parts of an utterance the cognitive-linguistic planning for the following words is not yet finished. Thus, different theories and methodological approaches support the assumption that temporal discoordination is involved in stuttering. However, experimental evidence for temporal differences between persons who stutter and persons who do not stutter in cognitive coding of phonological, semantic and syntactic information was lacking. Therefore, the monitoring experiment (see Table I and following section) was performed in order to investigate whether persons who stutter process some aspects of language in a way that can lead to temporal discoordination in speech planning and execution (see also Bosshardt, 1995b).

Demands and capacities framework

The "demands and capacities" theory was proposed by Adams, Starkweather and others (Andrews et al., 1983; Starkweather, 1987; Adams, 1990; Starkweather & Gottwald, 1990; Starkweather, 2002). In this view fluency deteriorates as a consequence of an imbalance between the child's capacities for maintaining fluency and self-imposed or external demands, like time pressure to respond quickly, the need to formulate complex sentences, speaking with anxieties, etc. Capacities include motor abilities (control speech movements smoothly and rapidly), linguistic abilities (formulation and planning of speech), socio-emotional abilities (speech planning and execution under conditions of communicative and emotional stress), and cognitive abilities (awareness of the linguistic structure of spoken language and the ability to monitor own speech for adequateness).

The demands and capacities model is compatible with any of the theories mentioned so far and also provides a coherent framework for the description of clinically relevant factors (Manning, 2001). In a recent critique, Siegel (2000; see also Ingham and Cordes, 1997; Packman & Attanasio, 2004) showed that the explanations that can be offered with the demands and capacities model suffer from circularity because no measurement procedures have been developed for detecting mismatches between capacities and demands. This critique seems to be only partly justified. It is correct in that linguistic capacities were originally not sufficiently specified by the authors. However, psycholinguistic theories were developed to describe in detail which subprocesses are involved in the production of "normal" nonpathological speech and, hence, these subprocesses can be seen as "capacities" for fluent speech. In dual-task experiments demands can be introduced at certain points in time and the effects of the secondary tasks on speech fluency and other speech parameters can be investigated.

In the present research programme dual-task methodology was used to investigate which subprocesses that are relevant for fluent speech. In these experiments persons who stutter and persons who do not stutter were asked to perform a speaking task (word repetition or sentence production) concurrently with a secondary task. In contrast to earlier studies of other investigators, secondary tasks were used which also consisted of linguistic material. The present results suggest that current psycholinguistic theorizing about speech production and language processing must be modified in three important ways before it can account for the observed between-group differences and for problems in speech fluency and stuttering (for a review, see Bernstein Ratner, 1997).

The first conclusion is related to the frequently proposed assumption (e.g., Levelt, 1989; Garrett, 1990; Levelt, Roloefs, & Meyer, 1999) that speech planning can be treated as the output of "modular systems" (Fodor, 1983). Fodor assumed that the brain consists of highly automatic, informationally encapsulated neurophysiological systems. Modular systems are "encapsulated" in the sense that their activity is not influenced by concurrent activities in other parts of the system (for a critical discussion of the modularity issue, see also Lieberman, 2000: 7). Although the modularity assumption was originally proposed for stimulus input systems, it can easily be extended to speech production. It was found that in comparison to speakers who do not stutter, speakers who stutter showed greater interference between speaking and concurrent attention-demanding processing. These group differences suggest that individuals can differ in the extent to which their speech production system is organized along the principles of modular organization and that speakers who do not stutter and speakers who stutter are located at the extremes of such a dimension.

Another conclusion to be drawn from the present studies suggests that persons who stutter respond differently than persons who do not stutter when required to speak while they were concurrently performing a second task. When the processing load imposed by the speaking task could not be reduced (as in word repetition, see Table I) and when this speaking task had to be performed under concurrent processing load, the stuttering rate of persons who stutter increased to a greater extent than that of nonstuttering persons. Thus, the subclass of disfluencies which defines stuttering (sound prolongations, sound and syllable repetitions, and silent blocks) can be seen as resulting from interferences between cognitive subsystems involved in speech planning and articulation.

A final conclusion can be drawn from the fact that the two groups again behave differently when producing a sentence under dual-task conditions. In sentence production (see Table I) subjects are free to generate longer or shorter sentences with more or less semantic content. In this task, the length of sentences produced by persons who do not stutter was unaffected by concurrent processing load, whereas persons who stutter produced shorter sentences under these conditions. Secondary task performance of both groups was significantly reduced to a comparable extent when sentences had to be produced concurrently. Thus, it can be concluded that persons who stutter tend to reduce the amount of concurrent processing by reducing the length and content of verbal productions.

In summary, the results of the present research programme suggest that subprocesses involved in speech planning and production are modularized to a lesser extent in persons who stutter than in person who do not stutter. It is further suggested that the lesser degree of modularization is responsible for higher stuttering rates. Finally, it is proposed that persons who stutter regulate the amount of concurrent processing by reducing the length and content of their verbal productions. Theoretical and therapeutic implications of these results will be presented in the conclusion section.

The following parts of the presentation are organized along the experimental paradigms. Table I presents an overview of the experimental paradigms to which the following sections will refer. Each paradigm will be explained in greater detail in the corresponding section.

Differences in monitoring times between persons who do and do not stutter

Bosshardt and Fransen (1996) designed the monitoring experiment in order to investigate whether persons who stutter and persons who do not stutter differ in verbal coding times. Based on earlier research (e.g., Bosshardt, 1990, 1993) it was hypothesized that persons who stutter code semantic and phonological information more slowly than persons who do not stutter and that these differences in verbal coding times are independent of differences in motor efficiency. The monitoring paradigm (see Table I) can be used to investigate this question because no overt verbal responses are required. While silently reading a prose text, participants monitored target words which were specified in advance of the presentation of the text. Participants pushed a button when they identified the target word. The target words to be monitored were either phonologically similar, categorically related, or identical to a cue word. Monitoring times for identical words were considered as base rate measures of reading and sensory-motor speed. The time difference between monitoring times for categorically related and for identical words was taken as a measure of semantic coding rate. In a similar vein, the time difference between monitoring for phonologically related and identical words was taken as a measure of phonological coding rate. The influence of syntactic information on word-monitoring reaction time was studied by presenting the text either as normal prose, in a syntactically correct but semantically anomalous version, or in a random word order. Fourteen adult persons who stutter and 14 adult persons who do not stutter participated in a self-paced word-by-word reading experiment. The two groups were closely matched for age, educational level, rated daily reading time, age and scores on a verbal fluency and a vocabulary test. The two groups were not different with respect to the speed of word identification. But for persons who stutter the time difference between category and identical-word monitoring was significantly greater than for persons who do not stutter. These results were taken to indicate that persons who stutter retrieved semantic information more slowly than persons who do not stutter.

The results of the monitoring paradigm cannot readily be interpreted from a motor control perspective: no overt verbal response was required and under all experimental conditions the same button pushing response was required. Therefore, Bosshardt and Fransen (1996) concluded that persons who stutter are slower than nonstuttering persons when they *cognitively process semantic verbal material*. From a motor control perspective it could be argued that this slower cognitive processing is an adaptive consequence of the slower speech movements of persons who stutter. However, this interpretation cannot account for the fact that specifically semantic processes were slower in persons who stutter than in persons who do not stutter, whereas word identification was not slower or was slowed to a much lesser extent. One conclusion to be drawn from this investigation is therefore that in addition to possible between-group differences in motor control, the two groups differ in the rate at which they cognitively encode semantic information.

Speaking with concurrent cognitive processing: differences between persons who do and do not stutter

Rationale of the dual-task paradigm

As suggested by Perkins et al. (1991) processing difficulties at the semantic (Wingate, 1988; Bosshardt, 1993; Bosshardt & Fransen, 1996) or phonological level (Wingate, 1988; Postma and Kolk, 1993; 1997) can desynchronize the speech plan and result in observable stuttering events. However, such a desynchronization process could only be directly investigated if it were possible to experimentally manipulate the rate of verbal coding processes during speaking. Unfortunately no procedure is known by which such an experimental variation of the coding rate during speaking could be realized. Therefore the effects of coding difficulties on speech were here investigated more indirectly with a dual-task paradigm.

Participants in dual-task experiments are instructed to speak concurrently with a secondary task. Performance in both tasks can remain unimpaired under these conditions as long as both tasks draw on different cognitive resources. Dual-task experiments with nonstuttering speakers (Power, 1985; Jou & Harris, 1992; Rummer, 1996) suggest that the generation of ideas and semantic content are attention-demanding activities whereas syntactic, phonological and articulatory processes do not seem to be affected by secondary tasks. Based on these results, Gathercole and Baddeley (1993) concluded that the central executive system as a limited-capacity system is involved in semantic and lexical planning because it coordinates the information flow between different processing levels.

With appropriately chosen secondary tasks it can be investigated in what way the speech of people who do and who do not stutter is affected by the load imposed by the secondary task. On this background four dual-task experiments were designed to study how additional attention-demanding coding processes affect speech fluency of stuttering and nonstuttering persons (see Table I). In contrast to earlier dual-task studies with stuttering persons, in the present experiments verbal-linguistic tasks were used as secondary tasks. The secondary tasks were selected so that they presumably draw on those parts of the cognitive processing system which are specifically involved in speech production (see Bosshardt, 1999, for details).

Continuous word repetition and sentence production were used as speaking tasks in separate experiments (cf. Table I). In continuous word repetition participants were required to overtly and continuously repeat a specific sequence of three words. In this speaking task, it is presumably verbal short-term memory, phonetic coding and articulation subsystems that are primarily involved. Sentence production tasks, by contrast, involve comparatively more cognitive systems because participants were required to generate and produce sentences that contain two specific nouns. We investigated how the performance of persons who stutter and persons who do not stutter was affected by secondary tasks. For this comparison we used two variants of the sentence-production task. In immediate sentence production (see Table I), subjects were required to overtly produce the sentence as soon as the two nouns which had to be included in the sentence were presented. In immediate sentence production, generation of sentence content and overt production are presumably performed concurrently. In the delayed sentence production task (see Table I), generation of content and overt production are separate. After presentation of the nouns to be included in the sentence, persons were given some time to silently generate sentence content before they were instructed to overtly produce it. It was assumed that under the delayed condition sentences were articulated with less concurrent cognitive processing from content generation than under the immediate-production condition.

Word repetition under dual-task conditions

Bosshardt (1999, 2002) investigated how cognitive coding and memory processes as secondary tasks affect the fluency of concurrently repeated words. In both experiments, word repetition was used as a speaking task (see Table I). The two experiments differed in that either mental calculations (Bosshardt, 1999) or silent reading and memorizing of words (Bosshardt, 2002) were used as secondary tasks to be performed concurrently with word repetition (see also Table I). A significant task by group interaction was only found in the latter experiment; these results will be presented first. In this experiment the words which had to be silently read or memorized concurrently with word repetition were phonologically similar or dissimilar to the words in the repetition task. Fourteen adult persons who stutter and 16 persons who do not stutter participated in the experiment. The two groups were matched for age, education, sex, memory span (forward and backward), and performance in a vocabulary test. It was found that persons who stutter had significantly higher stuttering rates during word repetition when they concurrently read or memorized similar words. This interference was more pronounced for similar than for dissimilar words. In contrast, the stuttering rates of persons who do or do not stutter were not significantly affected by either of the secondary tasks. These results were taken as an indication that the speech of persons who stutter is more sensitive to interference from concurrently performed cognitive processing than is that of persons who do not stutter.

In Bosshardt's earlier experiment (Bosshardt, 1999), mental calculation was used as a secondary task concurrently with word repetition as a speaking task. Under these conditions significant between-group differences in the *variance* of the stuttering rate were found under dual- but not under single-task conditions. Under dual-task conditions the between-subject variability of the stuttering rate was significantly greater within the stuttering group than within the nonstuttering group. This increased variability of the stuttering rate was largely due to the fact that only some stuttering persons showed an extremely high increase in stuttering rate under dual-task conditions whereas others showed only comparatively small increases. Thus, the speech of some persons who stutter was extraordinarily sensitive to interference from concurrent mental calculations whereas in others the stuttering rate increased to a lesser extent comparable to that of persons who do not stutter.

The results of the two word-repetition experiments together indicate that the speech of stuttering persons is sensitive to interference from concurrent attention-demanding activities, particularly when phonological processes are involved. Mental calculation, word reading and memorizing had different effects on the stuttering rate of persons who stutter. These differences indicate that in addition to the attention-demanding processing of phonological material further conditions are necessary to make these processes interfere with the fluency of word repetitions by persons who stutter. It is known that nonstuttering speakers largely use phonological codes to perform mental calculations (e.g., Logie, Gilhooly, & Wynn, 1994; Noel, Désert, Aubrun, & Seron, 2001), and that they flexibly use various cognitive strategies to solve these tasks (Carroll, 2000). The assumption that mental calculation tasks offer so many strategic options may be the reason that this secondary task only affected the fluency of word repetition in some of the stuttering speakers.

In summary, the results of the word repetition experiments suggest that the speech of persons who stutter is more sensitive to interference from concurrently performed cognitive processing than that of nonstuttering persons. Presumably, the phonological and articulatory systems of persons who stutter are protected less efficiently from interference by attention-demanding processing than that of persons who do not stutter.

Sentence generation and production under concurrent cognitive processing

Word repetition is a highly automatic speaking task and the results obtained with this task must not necessarily apply to other less repetitive and automatized speaking tasks. Therefore it was also investigated how sentence generation and sentence production of persons who stutter and persons who do not stutter are affected when performed under single- or dual-task conditions. Two sentence-production experiments (de Nil & Bosshardt, 2000; Bosshardt, Ballmer, & de Nil, 2002) were performed in which participants were required to form sentences using two unrelated nouns (see Table I). No restrictions were placed on sentence generation other than that the two nouns had to be used in the order presented. The two experiments differ in that in the immediate-production experiment participants were required to overtly produce a sentence as fast as possible after the two nouns for the sentences were presented (see also Table I). In the delayed-production experiment, sentence generation and articulation were separated so that in the generation part participants silently planned the sentence but were not allowed to overtly articulate it before the beginning of sentence production was signalled (see Table I). The results of both experiments will be presented in turn.

Immediate sentence production experiment

In the immediate-production experiment (Bosshardt et al., 2002) sentence generation and overt articulation were not separated. Under dual-task conditions, continuous rhyme and category decisions were used as secondary tasks. The category decisions involved a judgement as to whether or not two consecutively presented nouns belonged to the same semantic category or not. In the rhyming task participants were instructed to decide whether the current word rhymed with the preceding one or not. Participants indicate the results of their decisions by pushing one of two buttons. Fourteen adult persons who stutter and 16 persons who do not stutter participated in the immediate-production experiment. The two groups of participants were matched for age, education, sex, and scores on a written version of memory span (repeating numbers forward and backwards), and on a vocabulary test. Dependent variables were the number of correct rhyme and category decisions, decision latencies, length, number of propositions, sentence latency, speaking rate of sentences, disfluencies and stuttering rates. The results indicated that in both groups the average number of correct rhyme and category decisions was reduced when this task was performed concurrently with sentence generation and production. Similarly, the two groups of participants did not differ with respect to the correctness and latency of their decisions. Under single-task conditions the sentences of both groups had a comparable number of content units (propositions). But under dual- as compared to single-task conditions the number of content units produced by persons who stutter was significantly reduced whereas persons who do not stutter did not show a significant dual- vs. single-task contrast. Experimental conditions did not significantly influence stuttering rates.

These results suggest that sentence generation and production required greater sustained attentional processing in stuttering than in nonstuttering persons. Since the stuttering rate was lower for sentences with one propositional content unit (6%) than those with more units (10%) it seems that under dual-task conditions persons who stutter keep their disfluency rates at a constant low level by reducing the number of propositional units of their sentences. The results support the view that the speech production system of persons who stutter is more vulnerable to interference from concurrent attention-demanding semantic tasks. However, the results of this experiment also suggest that an increase in cognitive processing must not necessarily result in an increase in the number of disfluencies but rather can also lead to measures which reduce the amount of concurrent processing demands. Persons who stutter reduced the attentional demands of sentence generation and production by reducing the amount of "conceptual work" invested in speaking.

Delayed sentence production—an fMRI-study

A first attempt was made to investigate whether the stuttering person's linguistic processing is more vulnerable to concurrent cognitive activities during sentence generation or during overt articulation. In a delayed-production experiment participants produced sentences in two successive phases (cf. Table I). In the sentence-generation phase of the experiment, participants were required to cognitively generate a sentence which they were not allowed to overtly articulate before the beginning of the articulation phase was signalled. This paradigm makes it possible to investigate whether sentence generation affects performance in concurrent tasks in a different way than sentence articulation.

A delayed-production experiment was developed and functional resonance images were made during sentence generation and articulation under single- and dual-task conditions (de Nil & Bosshardt, 2000). Continuous rhyme and category decisions were used as secondary tasks. In this delayed-production experiment participants were instructed to silently generate their sentences for 10s before they were allowed to orally produce them. The experiment was run with 12 stuttering and 12 nonstuttering English-speaking male persons in Toronto. The two groups of participants were matched for age, education, scores on a written version of memory span test (repeating numbers forward and backwards), and for handedness. Neural activation was imaged using a 1.5 Tesla whole-body MRI scanner. Functional brain scans (TR=2), based on 25 sagittal scans (5mm width with a 1mm inter-slice gap), were overlaid on an anatomical scan. Imaging data were analysed using the fMRI module of Statistical Parametric Mapping (Wellcome Department of Cognitive Neurology).

No significant group differences were found for sentence length, number of propositional units and disfluency rates. Both groups showed similar reductions in length and number of propositional units under dual- as compared to single-task conditions. This latter result again confirms that sentence production and the two decision tasks draw on overlapping processing resources. However, in this delayed-production experiment, statistically reliable group differences were found in rhyme and category decision accuracy. Under dual-task conditions, stuttering persons showed a highly significant decline in their rhyming accuracy during sentence generation and articulation whereas the reduction in rhyming accuracy was not significant for the group of nonstuttering persons. Both groups of persons were equally adept at performing rhyming and category decisions as a single task with high accuracy. For both groups, category decision accuracy was reduced significantly during sentence generation. This accuracy reduction results from the overlap in semantic processing between category decision-making and sentence formulation. Overall, under dual-task conditions stuttering participants were less able than nonstuttering persons to maintain a high performance level simultaneously in sentence generation and production on the one hand and in the decision tasks on the other hand.

FMRI-data were collected both during the generation and during the articulation phase of the experiment. During single-task sentence planning it was found that persons who do not stutter showed increased activation in cortical areas associated with motor and semantic planning (primarily left supplementary motor area, superior parietal and cerebellar cortex). The persons who stutter also showed activation in some of these areas, but in addition showed activation in cortical areas that suggest increased pre-articulatory neural activation (bilateral prefrontal cortex, including left Broca's area). Under dual-task conditions, when subjects had to plan sentences simultaneously with making rhyming or category decisions, the group of nonstuttering subjects showed a similar pattern to that seen in the single-task sentence planning task with the exception of higher activation in premotor (dual-task rhyming) and anterior cingulate cortices (dual-task category condition). Activation maps of the group of persons who stutter showed comparatively higher activations in cortical areas related to motor planning and execution (left inferior and middle frontal cortex, premotor cortex and cerebellum).

These results suggest that both during sentence generation and articulation, persons who stutter activate cortical areas which are known to be involved in speech motor control. This greater overlap between the neurological substrates involved in speech planning as well as in articulation is consistent with previous positron emission tomography studies (de Nil, Kroll, Kapur, & Houle, 2000) and with clinical observations of increased articulatory involvement in stuttering speakers during silent speech. The activation of speech motor areas both in sentence generation and articulation was taken as an indication that persons who stutter use similar neural systems in both tasks. This overlap in the neural resources of sentence generation and articulation can be seen as an explanation for the greater sensitivity of stuttering speakers to interference between speaking and concurrent cognitive processing. On the basis of dual-task studies with sequential finger movements, Webster (1997) had already made a similar proposal (for details, see Bosshardt, 2002). But the study of de Nil and Bosshardt (2000) was the first to substantiate this hypothesis for sentence generation and production.

The results of the immediate- and delayed-production experiments together strongly suggest that persons who stutter need more central processing capacity to generate and overtly articulate a sentence than persons who do not stutter. In the immediate-production experiment it was found that the amount of semantic planning is one of the parameters which stuttering persons can use to reduce processing demands. In the delayed-production experiment it was found that persons who stutter can alternatively maintain the propositional content of their speech when they reduce the processing load imposed by a secondary task.

Conclusions

The present results show that there are individual differences in the extent to which the subsystems involved in speech planning are modularized, i.e., "encapsulated" from concurrent processes in other parts of the system. This conclusion is supported by results which show that in stuttering persons the subsystems involved in linguistic processing are less effectively protected against interfering influences from concurrent activities in other parts of the cognitive system.

In a recent study Oomen and Postma (2002; see also Postma, 2000) found in speakers who do not stutter that the efficiency of speech-error detection is significantly lower when speaking under dual- than under single-task conditions. Thus, error detection needs attentive control. However, Oomen and Postma's data showed that under dual-task conditions the number of speech errors increased by 88% whereas the efficiency of error detection was only reduced by 9%. Thus, the total number of speech errors increased to a much greater extent than would be expected on the basis of the reduction in monitoring efficiency. Therefore, it seems unlikely that the reduced efficiency of error detection can account for the increase in speech errors under dual-task conditions. Speech monitoring theory as proposed by Oomen and Postma is therefore not considered to provide a defendable alternative interpretation of the present results. Moreover, the reduction in the amount of semantic work which was found in sentence production under dual-task conditions can also not be readily accounted for by a speech monitoring theory. Therefore, at the present time the preferred assumption is that persons differ in the "robustness" of their speech-processing system to interference from concurrent processes in different parts of the system.

The interpretation of the present results can be related to a capacity construct as originally proposed by Andrews and Harris (1964 see also Andrews et al., 1983: 239). Andrews et al. (1983) proposed that the tendency to stutter habitually depends on the neurological capacity for sensory-motor transformations relative to the demands of the speech act. One possible way to model this imbalance has been proposed by Nudelman and colleagues (Nudelman, Herbrich, Hess, Hoyt, & Rosenfield, 1992). They assume that stuttering results from instabilities within a multi-loop speech-control system. They obtained no indication that stuttering and nonstuttering persons differ in their "primary sensory motor processing time" (p. 1888), but found that stuttering persons spend more time than nonstuttering persons at the detection of changes in the auditory signal. Nudelman et al. (1992) found a longer processing time in an "outer" cognitive control loop in persons who stutter. They assumed that this outer loop is responsible for the generation of linguistic information and that the greater instability of the control system in speakers who stutter is a result of the longer processing time.

With a totally different methodology, Bosshardt and Fransen (1996) obtained converging evidence showing that stuttering persons were slower in processing semantic content than nonstuttering persons. Thus, one possible way by which otherwise independent parts of a speech control system can become unstable is when they are coupled with critical phase lags. On the background of our fMRI-results an alternative interpretation has been proposed that in stuttering persons parts of the speech production system are based on neural structures which overlap to a greater extent than those of nonstuttering persons. From our present knowledge there is no reason to prefer one to the other interpretation.

In word repetition and sentence generation tasks it was found that with increasing cognitive processing load either the disfluency rate increases or linguistic productivity decreases. These results indicate that linguistic productivity could be an important variable in therapy. In this vein, it is important to note that prolongation is an efficient but not the only way to induce fluent speech (Riley & Ingham, 2000; Onslow, Bernstein Ratner, & Packman, 2001). Riley and Ingham found that children who were successfully treated with an extended length of utterance programme (Ingham, 1999) spoke fluently without prolonging their speech, whereas children who were treated with speech motor training (Riley & Riley, 1999) showed a significant increase in vowel duration. Similarly, one of two boys who were successfully treated with a stuttering contingent time-out procedure reduced his verbal output and lexical diversity whereas the other reduced his speech rate (Onslow et al., 2001). These results demonstrate that speech prolongation is not the only route to fluent speech and that techniques for cognitive control of processing load could open alternative routes.

The results of the present research encourage development of a therapy technique which is based on a dual-task methodology. Tasks which are to be performed concurrently with speaking reduce the time available for speech generation and thereby force speakers to insert pauses and to segment their speech into smaller units. In principle it seems possible that speaking under dual-task conditions can be used to increase the speakers' tolerance for pauses and his ability to produce shorter stretches of speech. From a clinical point of view, all these skills very likely increase speech fluency. The development and evaluation of such techniques seems to be a very important task for future research.

The present research raises more questions for future research. One question is whether and in what way variations in processing load affect the execution of speech movements.

Kleinow and Smith (2000) found that with increasing syntactic length of the utterance the stability of lip movements over multiple repetitions of the target phrase decreased in persons who stutter but not in persons who do not stutter. This suggests that the stability of speech motor control in adults who stutter is susceptible to linguistic complexity and hence to processing load. However, since Kleinow and Smith defined stability over multiple repetitions the implications of their results for a single utterance still need to be demonstrated.

Another important question for future research is related to the developmental nature of stuttering and how the effects that we observed in adult speakers may have developed in the course of language acquisition. It seems to me that the developmental conditions which according to the demands and capacities approach lead to stuttering are not favourable to the development of modular subsystems for the planning and execution of speech movements. In order to test this assumption empirically it is necessary to study how children who stutter and who do not stutter cope with enhanced processing loads.

Limitations

The present results were obtained with adult subjects, but stuttering is a disorder which characteristically develops in childhood between the ages of 2 and 6 years. The present observations can therefore be seen as a result of a lifelong experience with stuttering and treatment of stuttering (see also Conture, 2000: 6). However, the results of the present research programme are compatible with frequently reported results that the probability of stuttering increases with increases in utterance length and complexity. Such a relationship has been found in children (e.g., Bernstein Ratner & Sih, 1987; Logan & Conture, 1997; Yaruss, 1999; Melnick & Conture, 2000) and in adults (Jayaram, 1984; Bosshardt, 1995a; but see also Silverman & Bernstein Ratner, 1997). On the assumption that processing demands increase with increasing utterance length and complexity, these results support the assumption that the speech of stuttering persons in comparison to nonstuttering persons is more sensitive to interference from concurrent processing load. This argument shows that processing overload can reasonably be considered a causal factor in the development of stuttering. However, this argument can only be used temporarily to bridge our ignorance. It is necessary in any case to empirically investigate the effects of repeated exposure to processing overload conditions and to study the learning and adaptive processes which repeated exposure induces.

Another limitation of the present approach results from the fact that until now no data are available which make it possible to specify a mechanism which creates more stuttering-like disfluencies (word, syllable, and sound repetitions, prolongations, and blocks, see Yairi, 1997; Yaruss, 1998) when operating under enhanced processing load. For example, Kalveram's model of speech motor control (2000) specifies in detail how speech sounds are serialized and how this process is coordinated by auditory and efferent feedback. This model is sufficiently detailed to specify conditions under which less typical or typical disfluencies occur. This model could serve as a starting point to develop assumptions about how processing overload affects its components (word storage, shift-register, central pattern generator, and the feedback loop) and to derive testable predictions.

The final point is related to the fact that the fine-regulation of sensory-motor coordination under dual-task conditions has not yet been investigated in detail. In a word repetition experiment (Bosshardt, 1999) it was found that under dual- as compared to single-task conditions both stuttering and nonstuttering persons articulated the words more slowly. Thus, the speech of both groups seems to be slowed down in a comparable way under enhanced processing load. Ackermann, Wildgruber, Riecker, Hertrich, Dogil, and Grodd (2001) found that basal ganglia (primarily the left putamen) and the cerebellum were differentially involved at different speaking rates. Generalizing from these results (which were obtained with syllables) to word repetition, it can be hypothesized that changes of articulation rate activate different neurophysiological systems. Under dual-task conditions, this involvement of different systems could reduce the amount of interference between the two tasks because additional neural resources are recruited. However, within such a theoretical framework it remains to be determined why persons who do not stutter are more efficient in recruiting additional neural resources under dual-task conditions than persons who stutter.

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