WHY DOES SSTUTTERING DISAPPEAR WHEN ONE'S OWN SPEECH IS NOT HEARD? EXTERNAL AND INTERNAL AUDITORY FEEDBACK AND THEIR IMPACT ON STUTTERING.

by

Torsten Hesse

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Abstract

Neurological findings suggest that auditory feedback is used in speech control less effectively by individuals who stutter, as compared with normally fluent speakers; therefore, insufficient auditory-motor integration has been hypothesized to be a causal factor in stuttering. On the other hand, people who stutter are usually fluent when they do not hear themselves speak. This suggests that auditory feedback is irrelevant for speech control and even harmful for individuals who stutter. The present paper proposes an explanation for these seemingly conflicting observations.

It is assumed that speech feedback in the auditory modality is necessary for the control of fluent speech. When no external auditory feedback is available, e.g., because of masking by noise, speech control shifts to an internal feedback loop that provides predictions of the auditory consequences of speech motor commands to the speech comprehension system. In this way, one's own speech is heard internally. The use of this internal 'auditory' feedback saves from stuttering because of a close coupling between speech production and speech perception. However, the internal feedback loop works only if no external auditory feedback is available. Therefore, the internal feedback loop cannot compensate for insufficient integration of external auditory feedback in normal conditions, i.e., when one's own voice is heard during speech.

Consequently, the hypothesis that insufficient integration of auditory feedback is a causal factor in developmental stuttering is consistent with the fact that stuttering disappears when one's own speech is not heard.

1. Introduction

It has been known for a long time that developmental stuttering is strongly influenced by changes in auditory feedback. The way a person who stutters hears him- or herself speak can markedly reduce stuttering (see Bloodstein & Bernstein Ratner, 2008, for an overview). However, the role auditory feedback plays in stuttering is poorly understood until now.

In the last two decades, empirical findings have supported the view that auditory feedback is not involved in speech control in people who stutter (PWS) as intensively as in normally fluent speakers. Adults who stutter were found to exhibit weaker and/or delayed compensatory responses to unexpected perturbations of auditory feedback as compared with normally fluent controls (Bauer et al., 2007; Cai et al., 2012, 2014; Daliri et al., 2018; Loucks, Chon, & Han, 2012; Nudelman et al., 1992; Tourville, Cai, & Guenther, 2013). Neuroimaging studies showed that secondary auditory areas are mostly underactivated during speech in PWS, compared to normally fluent controls (see, e.g., meta-analyses by Brown et al., 2005, and by Budde, Baron, & Fox, 2014). These cortical areas, located mainly in the left superior and middle temporal cortex are assumed to be responsible, among others, for the self-monitoring of speech (e.g., Indefrey, 2011; McGuire, Silbersweig, & Frith, 1996; Price et al., 1996). In other neuroimaging studies, reduced auditory-motor coupling was found in adults who stutter during speech (Kell et al., 2018) and in children who stutter in resting state (Chang & Zhu, 2013). Several authors therefore concluded that PWS seem to poorly monitor the auditory feedback of their speech (e.g., Braun et al., 1997; Fox et al., 1996; Ingham et al., 2003; Kell et al., 2018).

As is well known, stuttering is markedly reduced in some special conditions, e.g., in choral speech, in speaking paced by the beat of a metronome, or in singing. In functional neuroimaging studies (Braun et al., 1997; Stager, Jeffries, & Braun, 2003; Toyomura, Fujii, & Kuriki, 2011), the effect of those fluency-evoking conditions on the brain activation in PWS was investigated. Consistently, auditory association areas were found to be greater activated in fluency-evoking conditions, compared to normal, i.e., stuttering-evoking conditions. Stager and colleagues conclude that “a common fluency-evoking mechanism might relate to more effective coupling of auditory and motor systems – that is, more efficient self-monitoring” (p. 319).

Furthermore, Daliri and Max (2015) found that normally fluent adults consistently showed a modulation of the auditory system prior to speech onset, but this modulation was greatly reduced or absent in adults who stutter. Max and Daliri (2019) hypothesize that this pre-speech auditory modulation plays a role "in engaging or even enhancing processes involved in sensory feedback monitoring" (p. 3074), and that it reflects "neural processes involved in priming and selectively biasing the auditory system for its role in monitoring auditory feedback during speech production" (p. 3075).

Together, these findings suggest (1) that auditory feedback is relevant for the control of fluent speech, and (2) that poor processing of auditory feedback or poor auditory-motor coupling is a factor in the causation of stuttering. However, this hypothesis seems to be inconsistent with other empirical findings which instead suggest that auditory feedback is irrelevant for speech control and even harmful for PWS.

It has been known for a long time that stuttering is often reduced in the presence of loud noise. Shane (1955) as well as Cherry, Sayers, and Marland (1955) found that stuttering was markedly reduced or even eliminated when auditory feedback was masked by white noise of high intensity. This effect was confirmed in further studies (e.g., Garber & Martin, 1974, 1977; Maraist & Hutton, 1957; Martin & Haroldson, 1979).

Another way of speaking without auditory feedback is silent mouthing, also referred to as lipped or pantomime speech. Mouthing is articulation without phonation and without or with extremely low exhalation such that, different from whispering, no audible sound is produced by the air flowing through the vocal tract. Mouthing reduces stuttering by nearly 100% (Commodore, 1980; Commodore & Cooper, 1978; Hudock et al., 2015; Perkins et al., 1976). A further suggestion that auditory feedback is not necessary, but rather detrimental for speech fluency is the fact that stuttering is rare in deaf people and that lifelong stuttering disappeared after hearing loss (see, e.g., Van Riper, 1982).

Such being the case, the facts concerning auditory feedback seem to be paradoxical: On one side, it seems as if auditory feedback is necessary for speech control, but poorly used by PWS. On the other side, it seems as if auditory feedback is irrelevant for speech control and rather harmful for PWS.

This seeming paradox exists not only with respect to stuttering. Lee (1950) found that a delay in auditory feedback by about one syllable length (1/4–1/5 second) evoked speech disfluencies in healthy individuals; repetitions, prolongations, omissions, and other kinds of speech errors occurred (see also Fairbanks & Guttman, 1958; Venkatagiri, 1980). This so-called Lee effect suggests an important role of auditory feedback in speech control. However, the speech fluency of healthy individuals is not affected when their auditory feedback is completely masked by noise; for instance, Martin et al. (1984) do not report any disfluencies in their control group with noise of 80 and 100dB. This again suggests that auditory feedback is irrelevant for speech control. To resolve this seeming paradox is the aim of the present paper. Below, I will propose the following account:

- I start from the position that auditory feedback, that is, feedback of one's own speech in the auditory modality is necessary for the control of fluent speech, which is suggested by the Lee effect on normally fluent speakers.
- Auditory feedback can be provided to the speech comprehension system in two ways, namely via an external and via an internal feedback loop. The external loop is what is usually referred to as auditory feedback,
- The internal feedback loop directly connects speech production with speech comprehension in the brain. The internal loop is not impaired in PWS, but it works only if external auditory feedback is not provided, i.e., when one's own voice is not heard externally.
- Since both the feedback loops do not work concurrently, the internal loop cannot compensate for a possible deficit in the external loop in normal conditions, i.e., when one's own voice is externally heard.
- The hypothesis that poor involvement of external auditory feedback is a causal factor in developmental stuttering is consistent with the fact that stuttering disappears when no external auditory feedback is available.

2. Internal auditory feedback saves from stuttering

In silent mouthing as well as in speaking with complete auditory masking by noise, articulation takes place without auditory feedback being available. In this condition, one's own speech is perceived and monitored internally such that speech errors can be detected (e.g., Brocklehurst & Corley, 2011; Lackner & Tuller, 1979; Oppenheim & Dell, 2010, 2008; Postma & Kolk, 1993). One's own speech is perceived mainly in the auditory modality, that is, one's own voice is internally heard (Reisberg et al., 1998; Smith, Wilson, & Reisberg, 1995).

It is commonly assumed that the way one's own speech is internally heard during mouthing or with auditory masking is the same way as that in which one's own speech is internally heard during 'inner speech', e.g., during silent reading and verbal thinking. So, Postma and Kolk (1993), Oppenheim and Dell (2008), and Brocklehurst and Corley (2011) investigated error detection during inner speech by having participants speak overtly with auditory masking, and Oppenheim and Dell (2010, p.1147) distinguish between "inner speech without articulatory movements", on one hand, and "articulated (mouthed) inner speech" on the other, that is, they regard mouthing as a kind of inner speech.

Usually, PWS do not experience disfluency during inner speech. Prima facie, this fact seems to be trivial: they do not stutter because they do 'not really' speak. However, according to Tian and Poeppel (2010, 2012), inner speech depends on motor simulation, it is controlled by sequences of motor commands just as is overt speech. In the light of this model, it is not trivial but rather astonishing that PWS usually do not experience difficulty during inner speech. Given the similarity between 'true' inner speech (without overt articulation) and 'articulated inner speech' (mouthing, speaking with auditory masking), it is not implausible to speculate that the cause for the absence of stuttering is the same in all these conditions. Let us therefore have a closer look at inner speech.

Inner speech, "that little voice that people often hear inside their heads while thinking" (Oppenheim & Dell, 2008, p. 528) was investigated intensively in the areas of reading and writing ability, working memory function, and schizophrenia (see Alderson-Day & Fernyhough, 2015; Perrone-Bertolotti et al., 2014, for an overview). Researchers have distinguished two aspects or components of inner speech: a production aspect sometimes referred to as 'internal articulation' or 'subvocalization', and a perception aspect sometimes referred to as 'inner hearing' or 'auditory verbal imagery' (e.g., Hurlburt, Heavey, & Kelsey, 2013; Oppenheim & Dell, 2010; Tian, Zarate, & Poeppel, 2016). Others have simply distinguished between 'inner voice' and 'inner ear' (Smith, Wilson, & Reisberg, 1995; Smith, Reisberg, & Wilson, 1992).

Several models were developed to describe the connection between the production and perception of inner speech, such as Levelt's (1983, 1989) internal feedback loop, Baddeley's (1992) phonological loop. The current model is that proposed by Tian and Poeppel (2010, 2012). As mentioned above, inner speech is thought to be a motor simulation of overt speech with the motor commands being transformed into internal auditory perceptions by a simulation-estimation process. These internal auditory perceptions provide an internal feedback of the auditory consequences of motor commands. Speech feedback in the auditory modality can thus be provided in two ways, namely via an external and via an internal feedback loop. Below, I therefore distinguish between 'external auditory feedback' (which is usually called auditory feedback) and 'internal auditory feedback' which is perceived by the 'inner ear'.

According to the model proposed by Tian and Poeppel, inner speech depends upon a close coupling of motor and auditory system. Already Smith, Wilson, and Reisberg, (1995) found an 'inner-ear/inner-voice partnership' to be essential for inner speech, that is, a close coupling between speech production (formulation) and speech perception. The inner voice cannot work independently of the inner ear, thus inner speech is speaking and listening, both in one.

In overt speech, by contrast, coupling between production and perception is not essential because overt speech is usually produced for others, not for oneself. Listening to oneself seems to be unnecessary. However, auditory-motor coupling it is still necessary for the control of fluent speech, as the Lee effect indicates. Lacking partnership between speech production and auditory perception in PWS in normal conditions, suggested by the deactivation of auditory association areas and by the lack of pre-speech auditory modulation, may therefore contribute to the causation of developmental stuttering.

During mouthing, during speech with complete auditory masking by noise, or after hearing loss, PWS are fluent not because they do not hear themselves speak. They hear themselves speak internally and monitor their speech by their 'inner ear'. This inner ear/inner voice partnership, a close coupling between speech formulation and auditory processing seems to save from stuttering during 'true inner speech', i.e., during silent reading and verbal thinking as well as during 'articulated inner speech', i.e., during overt speech without external auditory feedback.

3. Internal feedback cannot compensate for a deficit in external feedback.

If the above assumption are correct, then a new question arises. If we assume (1) that auditory feedback can be provided in two ways, namely via an external and an internal feedback loop, (2) that a deficit in the external feedback loop (insufficient processing or integration of external auditory feedback) is a causal factor in stuttering, and (3) that the use of the internal feedback loop saves from stuttering by ‘inner ear/inner voice partnership’, then the question arises: Can the internal feedback loop compensate for a deficit in the external feedback loop? If so, then the assumption that a deficit in the external feedback loop is a causal factor in stuttering would be implausible because the internal loop could compensate for the deficit.

However, such a compensation is possible only if both, external and internal feedback loop work concurrently. Empirical findings suggest that this is not the case. Smith, Reisberg, and Wilson (1992) found that input from the ‘outer ear’ interfered with the use of the ‘inner ear’: The use of the inner ear was the more disrupted the more a concurrent external auditory input was phonologically similar to what would be heard internally. White noise, as it is not similar to speech, did not impair the inner ear, but externally presented speech stimuli blocked the perception of inner speech.

This suggests that the internal feedback loop does not work when one’s own speech is externally heard because the two signals are phonologically equivalent. This position is supported by Vigliocco and Hartsuiker (2002) who note that if internal and external auditory feedback worked concurrently, we would hear our speech twice, once by the ‘inner ear’ and once externally. Moreover, there would be a time lag between the two signals because external feedback needs more time than internal feedback (Lackner & Tuller, 1979; cf. Levelt, 1989).

Not least the Lee effect suggests that external and internal auditory feedback do not work concurrently. As already mentioned, a delay in the auditory feedback of speech by about 200ms evokes speech disfluencies in healthy individuals. Obviously, the internal feedback loop cannot compensate for the control problems caused by the delay in the external feedback. This is not surprising because external and internal signal are phonologically very similar despite the delay of the external signal. This explains the seemingly paradoxical fact that normal speakers are disfluent when their external auditory feedback is delayed by 200ms, but not when it is completely masked by noise. In the latter, but not in the former case, speech control can shift to the internal feedback loop.

3.1. The problem of pre-articulatory monitoring

The observations reported above strongly suggest that external and internal auditory feedback are not available concurrently. However, the question of whether or not both the feedback loops work concurrently seems to be linked to a further question, namely to the question of whether humans permanently monitor their speech internally prior to articulation. Such a pre-articulatory monitoring of internal feedback during overt speech has been assumed by Levelt (1989) in his perceptual loop theory which is still the standard model of the self-monitoring of speech (but see the criticism of that model by Nozari, Dell, & Schwartz, 2011). The perceptual loop theory assumes the concurrency of external and internal speech feedback. Levelt (1989) claimed that a "phonetic plan" is transferred through the internal feedback channel to the speech comprehension system. He did not explicitly claim that this plan is internally heard during overt speech, but the term 'phonetic' still suggests some kind of internal auditory perception or auditory imagery.

However, Wheeldon and Levelt (1995) revised this position. They came to the conclusion that not a phonetic but an abstract phonological representation is internally monitored during overt speech. It is unclear if and how a phonological representation is internally perceived in a sensory modality, and Wheeldon and Levelt admit that, in their experiment, participants possibly generated visual or graphemic instead of auditory representations for the purpose of internal monitoring. That means that the perceptual loop theory does not necessarily imply the monitoring of internal auditory feedback during overt speech.

There is further some evidence that no monitoring of internal sensory feedback takes place during overt speech: Huettig and Hartsuiker (2010) registered eye-movements while speakers named objects that were visually presented together with phonologically related or unrelated words. They found eye-movements to be driven by the perception of overt, but not inner speech. The authors conclude that there is no speech monitoring based on internal sensory perception. Lind et al. (2014) covertly manipulated their participants' external auditory feedback in real time so that they said one thing but heard themselves saying something else. In most cases, participants believed that they had said what they heard. The authors conclude that internal feedback is either unavailable during overt speech, or it is overridden by external auditory feedback.

This does not mean that pre-articulatory monitoring of speech does not exist. For example, Seyfeddinipur, Kita, and Indefrey (2008) and Nooteboom and Quené (2017) found very quick reactions to self-produced speech errors and interpret them as evidence for error detection prior to articulation. However, the pre-articulatory monitoring of speech seems to depend on another mechanism than internal auditory feedback. Nozari, Dell, and Schwartz (2011) proposed and tested a model of speech error detection which is not feedback- but production-based. They assume conflict monitoring at the time of response selection to be the basis of speech error detection.

Support for this view comes from electroencephalographic studies. An error-related potential (ERN = error-related negativity) was identified in manual motor tasks, but also in speech tasks (Ganushchak & Schiller, 2008; Ries et al., 2011; Trewartha & Philips, 2013). Findings suggest that ERN is not so much related to errors, but rather to conflict monitoring, e.g., during speech formulation (Ries et al., 2011;Trewartha & Philips, 2013). Therefore, quick responses to self-produced speech errors are no evidence for a monitoring of internal auditory feedback during overt speech and thus no evidence of external and internal auditory feedback to work concurrently.

Let us finally look at an ‘engineering model’ of speech motor control with concurrent external and internal auditory feedback, the State Feedback Control model (Hickok, Houde, & Rong, 2011; Hickok, 2012). The authors propose that internal forward models provide predictions of the auditory consequences of speech motor commands to the speech comprehension system. These internal predictions, so the authors assume, are earlier available for the comprehension system than external auditory feedback which, so the authors claim, is too late to be usable as the basis for timely error detection and online correction.

The State Feedback Control model implies that a person (or her brain) knows how her speech will sound like before she hears it externally. However, experiments (e.g., Cai et al., 2012; Loucks, Chon, & Han, 2012; Tourville, Reilly, & Guenther, 2008)) have shown that speakers compensate for manipulations of pitch in their external auditory feedback. This strongly suggests that speakers have no other information about the pitch of their speech than that provided by external auditory feedback.

The State Feedback Control model further claims that speech motor control is almost independent of external sensory feedback (Hickok, 2012). However, the Lee effect indicates the opposite. Delayed (external) auditory feedback would hardly impair speech flow if the speaker or his/her brain had internal information about the actual speech output earlier than that provided by external auditory feedback. If natural, non-delayed auditory feedback were too late to be relevant for speech control (as Hickok and colleagues assume), then delayed auditory feedback would be irrelevant even more and could not cause disfluency. Therefore, the Lee effect shows that the State Feedback Control model cannot be correct: During overt speech, speakers (and their brains) have no other information about their verbal output than that provided by external auditory feedback. This is confirmed by the above-mentioned findings of Lind et al. (2015).

Summarizing, we can assume that internal predictions of the auditory consequences of motor commands form the basis of internal auditory feedback. This enables us to hear our own speech internally when no external auditory feedback is provided. But internal auditory feedback is not available and plays no role in self-monitoring during overt speech as long as one's own voice is heard externally. Internal and external auditory feedback do not work concurrently; therefore, internal auditory feedback cannot compensate for deficits possibly existing in the processing or integration of external auditory feedback in PWS.

4. Summary and conclusion

The aim of this paper was to resolve the seeming conflict between two groups of empirical findings, namely (1) those suggesting poor processing or integration of auditory feedback to be a causal factor in developmental stuttering, and (2) those suggesting auditory feedback to be irrelevant for speech control and even harmful for PWS. To resolve this inconsistency, it was necessary to take into account the fact that speech feedback in the auditory modality can be provided in two ways, namely via an external and via an internal feedback loop. When external auditory feedback is not available, then (and only then) speech control shifts to internal auditory feedback.

Internal auditory feedback seems to be unimpaired in PWS, so that they do not experience disfluency in silent reading and verbal thinking, during mouthing, during overt speech when their own voice is masked by noise, or after hearing loss. That is, they are not fluent in these conditions because they do not hear themselves speak. Instead, they hear themselves speak internally, and stuttering does not occur because of the inner ear/inner voice partnership which is essential for the internal feedback loop, and which ensures a close coupling of speech formulation and auditory processing.

So there is no reason to assume that auditory feedback is irrelevant for speech control and harmful for PWS. Instead, we can assume that auditory feedback is necessary for the control of fluent speech (which is not least suggested by the Lee effect), and that a deficit in external auditory feedback, e.g., insufficient processing or integration of this information is a causal factor in developmental stuttering (as suggested by findings of brain research, see Introduction).

Empirical findings suggest that external and internal auditory feedback do not work concurrently. Therefore, internal auditory feedback, although unimpaired in PWS, cannot compensate for a possible deficit in external auditory feedback, in its processing or integration. Consequently, the hypothesis that stuttering is caused by a deficit in external auditory feedback is plausible despite the existence of an internal auditory feedback loop.

Future research should seek to figure out if there is a specific impairment in the external auditory feedback in PWS. There is growing evidence for an anomaly in central auditory processing in PWS (e.g., Arcuri, Schiefer, & Azevedo, 2017; Chang et al., 2009; Devaraju, Maruthy, & Kumar, 2020; Dietrich, Barry, & Parker, 1995; Hampton & Weber-Fox, 2009; Howell et al., 2000; Howell, Davis, & Williams, 2006; Jansson-Verkasalo et al., 2014; Kikuchi et al., 2011, 2017: Liotti et al., 2010; Neef et al., 2012; Salmelin et al., 1998; Saltuklaroglu et al., 2017). In some studies, a statistical correlation was found between poor or aberrant auditory processing and stuttering frequency or severity (Beal et al., 2010, 2011; Howell et al., 2000; Jansson-Verkasalo et al., 2014; Kikuchi et al., 2017; Liotti et al., 2010).

A further factor that may influence the processing of external auditory feedback is the allocation of attention during speech. The processing of auditory verbal input is depending on attention to the auditory perceptual channel (Cherry, 1955; Jäncke, Mirzazade, & Shah, 1999; Hugdahl et al., 2003; Sabri et al., 2008). This might be true not only for the processing of speech produced by others, but also for the processing of the auditory feedback of one’s own speech. This was demonstrated experimentally by Scheerer, Tumber, and Jones (2016) in a behavioral study with normal speakers.

The authors conclude that their results “suggest that attention is required for the speech motor control system to make optimal use of auditory feedback for the regulation and planning of speech motor commands.” (p. 826)

There is ample evidence of deficits in the control of attention in PWS (e.g., Alm, 2014; Anderson & Wagovich, 2010; Eggers, De Nil, & Van den Bergh, 2012; Eggers & Jansson-Verkasalo, 2017; Ntourou, Anderson, & Wagovich, 2018; Wagovich, Anderson, & Hill, 2020). Chang et al. (2018) investigated resting state connectivity in and between several intrinsic connectivity networks in the brain in children who stutter and controls. They found persistent stuttering to be associated with aberrant connectivity between default mode network and dorsal and ventral attention network. Kaganovich, Hampton Wray, and Weber-Fox (2010) conclude from an examination of auditory processing in preschoolers who stutter that stuttering may be associated with less efficient attention allocation.

Therefore, future research should investigate possible relationships between auditory processing, attention allocation during speech, and stuttering. Specific questions could be: Is there a relationship between a possible auditory processing deficit and auditory attention in PWS? Is, in PWS, pre-speech auditory modulation related to attention to the auditory channel prior to speech onset? Is stuttering frequency influenced by attention to auditory feedback?

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