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Effects of delayed auditory feedback on speech: just a problem of displaced rhythm?

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Introduction

A great number of studies have investigated the importance and the influence of feedback control on sequencing processes by manipulating sensory feedback. Some of those studies have been concerned with the effects of delayed auditory feedback (DAF) on normal speech production: Insertion of a delay between a spoken message and its audible feedback causes disturbances in speech control that are sometimes described as artificial stuttering (Black, 1951; Lee, 1950, 1951). This delayed auditory feedback effect was first described by Lee (1950) and is, therefore, also called the Lee Effect. In Lee's original work, an oral speech signal was delayed mechanically (up to 300 ms) before being returned to the speaker's ears via earphones. Disruptions of speech were observed on several dimensions, for example, in the overall speech time, speech rate, fluency, and articulation (Fairbanks, 1955; Fairbanks, and Guttman, 1958; Lee, 1950). DAF usually results in a considerable slowing down (Black, 1951; Chase, Harvey, Standfast, Rapin, and Sutton, 1959; Fairbanks, 1955; Lee, 1950; Spilka, 1954; Tiffany and Hanley, 1956) as well as increased disfluencies (Atkinson, 1954; Chase et al., 1959; Fairbanks, and Guttman, 1958). The amount of disruption is dependent on the size of the delay between the produced speech and the corresponding feedback, with its maximum at about 200 ms (Black, 1951; Butler, and Galloway, 1955; Fairbanks, 1955). The disturbance function of different delay times exhibits the shape of an inverted U. Whereas this U-shaped function holds for speech errors, pitch and level of the voice show different effects: Changes in these dimensions increase up to a delay of 200 ms, but then the function levels off rather than decreases. In addition, the amount of disruption has been found to vary with age, with DAF disrupting the speech of children more than of adults (MacKay, 1968; Siegel, Fehst, Garber, and Pick, 1980). Further individual factors are fluency, sex and whether the person is a native speaker or not. Males are more affected by DAF than females (Bachrach, 1964) and native language speakers show less disruption effects than speakers who acquired the language later in life (MacKay, 1970). A comprehensive overview of speech characteristics under DAF can be found in Röck (1977).

Similar effects of DAF were observed in sequencing of rhythmic finger movements (Chase, Sutton, Rapin, Standfast, and Harvey, 1961; Karlovich, and Graham, 1966, 1967; Rapin, Costa, Mande, and Fromowitz, 1963, 1966; Ruhm and Cooper, 1962), in clapping hands (Kalmus, Denes, and Fry, 1955), in playing organ and other keybord instruments (Gates and Bradshaw, 1974; Gates, Bradshaw, and Nettleton, 1974; Long, 1975) as well as in writing and painting (Smith, McCrary, and Smith, 1960; Van Bergeijk and David, 1959). Thus, the underlying mechanisms causing the Lee Effect are assumed to be general mechanisms of action sequencing.

DAF and stuttering. There is an ongoing debate on the question of whether the mechanisms leading to disturbances of speech in the DAF paradigm are similar to the mechanisms causing stutterers' speech or not. Research on family incidence of stuttering shows in some parts consistent findings with studies on the reactions of twins to delayed auditory feedback (e.g., Andrew and Harris, 1964; Timmons and Rankin, 1970). Further support for the hypothesis that effects of DAF on normal speakers have a physiological basis equivalent to that of stuttering is given by research on effects of age and sex (e.g., Chase, Sutton, First, and Zubin, 1961), stress indicators (e.g., Blanton and Blanton, 1936), and different speech characteristics. Most of these comparisons of stuttering and reactions to DAF consider neurological or conductance disturbances to be underlying factors (e.g., Chase, 1958; Fairbanks, 1955; Lee, 1950; Timmons and Boudreau, 1972; Webster and Lubker, 1968). Some studies deal with insufficient neurophysiological control of sensorimotor processes related to speech production (e.g., Zimmermann, 1980; Kalveram and Jäncke, 1987).

When stutterers are confronted with DAF, stuttering decreases drastically and speech becomes more fluent. As a consequence, DAF has been found to be a useful tool in speech therapy for stutterers (Goldiamond, 1966; Lotzmann, 1961; Soderberg, 1969; Timmons and Boudreau, 1978a, 1978b).

Theoretical accounts

Various theoretical accounts and models have been proposed to explain the effects of DAF. In the following, we will outline a selection of traditional assumptions concerning the Lee Effect. Although, at first view, these accounts seem fairly similar, they differ in their assumptions regarding the

The monitoring function of feedback. The "classical" approach, first presented by Lee (1950) and repeatedly tested in various studies (e.g., Postma, 1993; Black, 1951), proceeds from a "missing-feedback" assumption. The basic consideration is that auditory feedback helps control regular sequencing processes. Lee (1951) as well as other authors (Postma, 1993; Black, 1951) assumed the effects of delayed auditory feedback to be a result of waiting for an expected effect that doesn't occur. Thus, the feedback of the first part of a verbal action has to be received successfully before the second (or following) part of the action will be called up. This implies the existence of a monitoring process. In consequence, if an unexpected feedback is perceived under DAF conditions, the system stops and initiates again the first part of the utterance.

Correspondingly, the occurrence of prolongations and perseverations as a result of DAF is caused by the waiting position of the system. The observation that maximum disruption occurs at 200 ms can be related to the fact that the average length of a syllable is about 200 ms. In case of DAF, the speaker's intention to perform one syllable would be disturbed by simultaneously hearing what was produced on the preceding one. Thus, this hypothesis explains why effects on DAF are maximal at a delay of 200 ms.

Nevertheless, the monitoring assumption of the Lee Effect leaves some critical questions unanswered. Various studies demonstrated that susceptibility to DAF depends on strategies used by the participants to circumvent the experimental intervention (e.g., Bachrach, 1964; Siegel et al., 1980; Howell et al., 1983). The use of these strategies, and, in consequence, the varying susceptibility to DAF speaks against the monitoring account. This is also true for the finding that, at a delay of 200 ms, the disruption effects are exactly the same during production of speech or nonspeech sounds (Howell and Archer, 1984; Howell et al., 1983).

Interference and perseveration hypothesis. With these objections in mind, other authors have proposed an interference mechanism. According to Neumann (1982), the Lee Effect originates from an interference of two conflicting response tendencies during action planning. Neumann (1982) assumes that the delayed feedback of the first part of a verbal action interferes with the ongoing action planning of the second part, so that the underlying process in the Lee Effect is assumed to be a difficulty in response-selection.

A related, but more elaborated account has been proposed by MacKay (1987). According to his perseveration hypothesis, in normal speech production every spoken unit enters automatically a phase of self-inhibition followed by a phase of hyperexcitability. The Lee Effect is explained by the assumption that the critical feedback occurs during the hyperexcitable phase. In other words, the feedback produced by the spoken unit activates again the same verbal unit, thus eliciting the same utterance again and again (perseveration tendency). As a consequence, prolongations in the DAF paradigm could be explained as a strategy to avoid feedback during the hyperexcitability phase. Instead, the speaking person tries to shift the feedback into the phase of inhibition.

Displaced-rhythm hypothesis. Based on studies which replaced the normal speech feedback by nonspeech sounds comparable in intensity and rhythm, Howell and co-workers (e.g., Howell et al., 1983; Howell and Archer, 1984) formulated the displaced-rhythm hypothesis. The authors observed that DAF effects of speech and nonspeech sounds are in general identical (e.g., maximal disturbances at a delay of 200 ms) and therefore concluded that DAF effects originated only from the intensity profile of the (delayed) signal. This profile is necessarily shifted in time and, therefore, does not correspond to the ongoing speech any longer. Therefore, the authors suggested that the effects of DAF arise from an interference with the "performance of a serially organized behavior (such as speech), produced by a rhythmic event going on at the same time but out of synchrony with the activity" (Howell et al., 1984, p. 297). According to this account it is not the semantic identity of the delayed feedback signal but the asynchrony of the rhythm that causes the disturbances.

Evidence for the displaced-rhythm hypothesis comes from experiments in which the delayed feedback was identical in its rhythmic structure to the original speech. Specifically, in some conditions a nonspeech signal (a square wave) with the same intensity envelope as the original speech was substituted for the delayed speech signal. Performance in the DAF task was equivalent when feedback was a delayed version of the speaker's own speech or of the nonspeech sound. The factor determining disruption seems to be only when a sound occurs independent of its semantic content. In other words, it is important whether the rhythm is in accordance with the original speech, not whether the sound is speech or not (Howell and Archer, 1984).

An experimental study

In our laboratory the influence of phonetic identity and of rhythm was examined by delaying the feedback on sequences of syllables which either had no variation (/ta-ta-ta/; condition 1), variation in rhythm (/ta-ta-ta/ with stress on every second syllable; condition 2), variation in identity (/ta-ti-ta/; condition 3), or both (/ta-ti-ta/; condition 4). The amount of delay comprised exactly one syllable. On the basis of the displaced-rhythm hypothesis only those conditions should be sensitive to DAF (as compared to conditions without DAF) in which the sequence of syllables (and thus the feedback) includes a variation in rhythm (i.e., conditions 2 and 4). However, if the identity of the sound is critical, condition 3 should also reveal an influence of DAF.

Method

Stimulus material, apparatus, and procedure. Four sequences with consonant- vowel combinations consisting of either the syllable /ta/ or /ti/ were tested in four conditions. In condition 1 participants had to pronounce units of /ta/ without any accentuation; condition 2 contained the same units of /ta/, however, participants had to accentuate every other syllable starting with the first unit (/ta-ta-ta-ta.../). In condition 3 participants were again instructed not to accentuate any syllable but, different to condition 1, they had to pronounce the units /ta/ and /ti/ in alternating order (starting with /ta/). In condition 4, subjects had to perform units of alternating /ta/ and /ti/ with accentuation on /ta/. In all conditions, participants were paced by a binaural click (with white background noise) leading to a time interval between each unit of 410 ms. The white background noise was used to mask bone conduction. The interclick interval of 410 ms enabled the subjects to pronounce the syllables in a suitable pace. In addition, it allowed to present the delayed feedback in a way that it matched exactly with the production of the following syllable.

Conditions were presented blockwise with the order of blocks balanced across participants. Each block consisted of six trials, one trial in which the feedback was presented without delay was followed by five experimental trials with a feedback delay of 410 ms (leading to a shift of exactly one syllable). Within each experimental trial participants had to produce ten syllables. During the first four syllables normal feedback was given (part A). Only after the fifth syllable the delay was introduced (part B). Thus, participants received the feedback of the fourth syllable while pronouncing the fifth and so on.

The experiment was carried out on a laboratory computer (Hewlett Packard RS/20C) in a sound-absorbing room. A microphone-headphone combination (Sennheiser HMD 224) was used with a fixed distance of about 10 cm from the mouth to the microphone. Sound pressure level at 1000 Hz and 1 mW was 84 dB (= 450 mV at 200 Ohm). Oral output was delayed via the computer program, which also recorded all spoken sequences. Data were recorded by a data-translation card (DT 5712-PGH).

Participants. 12 participants (six females) took part in the experiment. All participants performed all conditions.

Data analyses. Produced sound sequences of each participant were analyzed by a computerized speech research environment (CSRE). For each spoken sequence the overall duration was calculated after exactly determining the on- and offsets. This procedure was performed for the whole sequences as well as for the parts of the sequences before and after the delay, respectively. The absolute values for each part (before and after the delay) were standardized by dividing them by the number of syllables performed. Individual mean voice level was calculated for each part of the sequence, before and after the delay.

Results

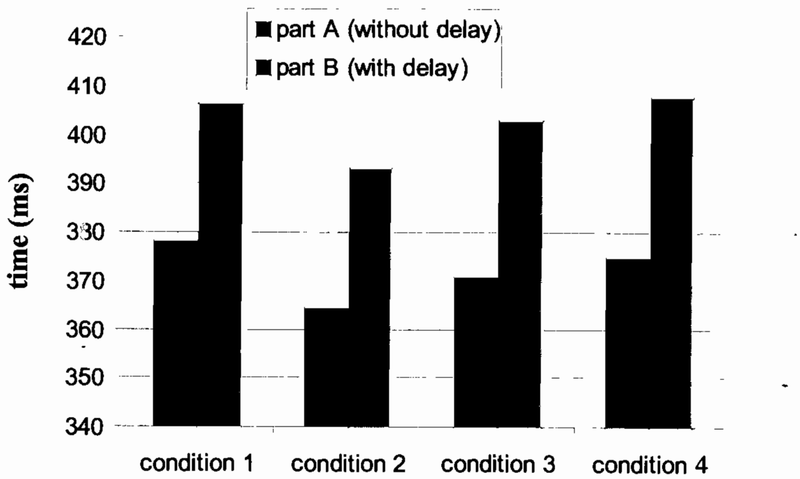

Figure 1. Mean produced sequence duration in ms for all 12 participants comparing part A (before inserting the delay) and part B (after inserting the delay). (Condition 1 = /tata/; condition 2 = /t̲a̲ta/; condition 3 = /tati/; condition 4 = /t̲a̲ti/).

Sequence duration. To test the effect of the delay, the duration of the spoken sequence of part A (before inserting the delay) and of part B (after inserting the delay) was examined for each trial separately. The difference in the number of produced syllables per part was taken into consideration by calculating a quotient between the absolute length of each part and the included number of syllables. Analyzing the mean produced sequence duration as dependent variable, a repeated measurement analysis of variance (ANOVA) with within-participant factors condition (four levels) and delay (part A vs. B, i.e., before and after inserting the delay) resulted in no significant main effect of condition [$F(3, 9) = 2.03$; $p = .179$], a significant main effect of delay [$F(1, 11) = 22.70$; $p < .001$], and no significant interaction [$F < 1$]. As can be seen in Figure 1, spoken sequence duration increased with the introduction of the delay, but not significantly different between the conditions.

Voice level. In addition to produced sequence duration, changes in the general voice level (volume) were analyzed. Individual mean voice levels (in Volt) of parts A and B within each trial were analyzed separately. Figure 2 shows means of the voice level before and after inserting the delay and compared between the conditions.

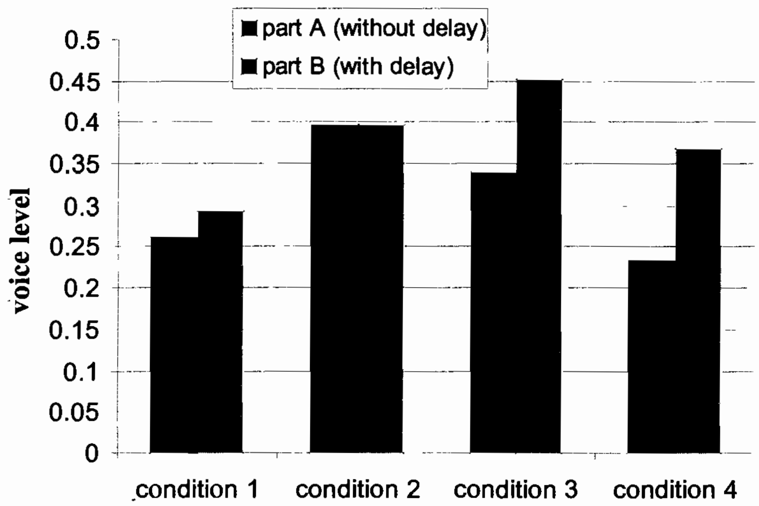

Figure 2. Mean voice level for all 12 participants comparing part A (before inserting the delay) and part B (after inserting the delay). (Condition 1 = /tata/; condition 2 = /tata/; condition 3 = /tati/; condition 4 = /tati/).

A repeated measurement ANOVA with the independent factors condition and delay exhibited a significant main effect of the factor condition [$F(3, 9) = 5.53$; $p < .02$], a significant main effect of the factor delay [$F(1, 11) = 7.06$, $p < .02$], as well as a significant interaction between both factors [$F(3,9 = 11.69$; $p < .002$] As Figure 2 shows, the delay of feedback results in an increase of the general voice level. An analysis of this effect within the conditions via paired t-test yielded significance in all conditions except condition 2 (condition 1: $t = 2.98$, $p < .01$; condition 2: $t < 1$; condition 3: $t = 2.98$, $p < .01$; condition 4: $t = 4.22$, $p < .001$). Additionally, calculations of post-hoc comparisons between the conditions showed significant differences between condition 1 and condition 2, condition 1 and condition 3 and between conditions 2 and 4, respectively ($p < .01$). Condition 1 exhibited the lowest voice level compared to the other conditions.

Discussion and conclusion

Under delayed auditory feedback speech control is disturbed, that is, voice level is enhanced and extra time is needed to perform a spoken sequence. These effects indicate that auditory feedback is essential for continuous control of speech production. However, it is still an ongoing controversy what aspect of the feedback produces the disturbance. The "displaced-rhythm hypothesis" (Howell, Powell, and Khan, 1983) proposes that the disturbances arise from the disruptive effects caused by the rhythm of the delayed signal. This hypothesis implies that the semantic content ("identity") of the delayed speech is of no importance.

In our experimental study, typical disturbances of speech production under DAF conditions were observed. The analyzed parameters were sequence duration and voice level depending on changes in rhythm and identity. A significant increase in sequence duration was found in all conditions, no matter if rhythm, identity, or both changed. Significant changes in voice level also showed up in all conditions, except for condition 2 in which only the rhythm changed. The latter finding contradicts the hypothesis that displaced rhythm is the only variable causing the Lee Effect, as Howell et al. (1983) claimed.

An influence of DAF expressed by changes in voice level could be demonstrated under conditions in which rhythm and identity were involved in delayed feedback. Here, too, identity turned out to be an important aspect in feedback that produced the DAF effects. Although our material consisted of meaningless syllables, the identity of the delayed feedback which was realized by changing the vowel specifying the /t/ constituted the correct or the disturbed performance in the sequencing as well as in the accents. As expected from a point of view that stresses the importance of the identity of the feedback, two different "contents" coming to temporal coincidence by employing delayed auditory feedback led to a confusion and, in consequence, to increased sequence duration in performing the sequence without involving rhythm in any way.

The finding that under DAF the "single identity condition" (3) and the "rhythm and identity condition" (4), showed an increase in produced volume whereas the rhythm condition (2) showed no change in voice level, is, at first sight, surprising. However, it possibly indicates that in the case where mainly rhythmic information is available, the rhythmic information in a spoken sequence can be used as a "frame" to keep the timing. If only rhythmic information is available, the "wrong" rhythm resulting from the delayed feedback does not seem to disturb the regular performance of the spoken sequence. Anyway, the results showed that the identity of the feedback has a strong influence on the performance of the spoken sequence.

As outlined above, some authors consider effects on DAF similar to speech errors in stuttering. If we adopt this stance and consider research in stuttering, we find many studies dealing with the influence of rhythm on the speech of stutterers. First, there is a lot of evidence that stuttering persons show deficits in the acquisition, reproduction, imitation and performance of rhythmic structures (e.g., Beech and Fransella, 1966, 1968; Fransella, 1965, 1967). Simultaneously, various studies show that rhythmic treatments reduce stuttering (e.g., Adams and Hutchinson, 1974; Conture and Brayton, 1975). Yet, it is not clear after all whether this effect is caused by a "distraction" function of rhythm or whether parameters like fundamental frequency or vocal duration are influenced. Third, but not last, stutterers' reactions to DAF which consist of a considerable reduction in stuttering (Goldiamond, 1966; Lotzmann, 1961; Soderberg, 1969; Timmons and Boudreau, 1978a, 1978b) resulted in research demonstrating that such feedback is a useful tool in speech therapy for stutterers (Curlee and Perkins, 1973; Goldiamond, 1966; Ryan and Van Kirk, 1974; Van Riper, 1973).

Our results show an influence of changes in identity on sequence length and voice level, but only in parts an influence of changes in rhythm on the same parameters. Our considerations in combination with these findings suggest that, in conclusion, displaced rhythm -among other factors- only is one of several factors that contribute to the well-known effects of delayed auditory feedback. Beyond that, rhythm can have a supporting function in performing regular speech sequences. Further studies with real speech sequences have to be performed to get more detailed information on the specific role of the several factors responsible for speech performance.

Summary

Under delayed auditory feedback of about 200 ms (DAF) speech control is disturbed, that is, frequency of speech errors is increased, voice pitch and level are enhanced, and extra time is needed to perform a spoken sequence. These effects indicate that auditory feedback is essential for continuous control of speech production. However, it is still an ongoing controversy what aspect of the feedback the disturbance produces. The "displaced-rhythm hypothesis" (Howell, Powell, and Khan, 1983) proposes that the disturbances arise from the disruptive effects caused by the rhythm of the delayed signal. This hypothesis implies that the semantic of the delayed speech is of no importance.

We tested this hypothesis with the following conditions: Participants had to perform sequences of 10 syllables each in which either the rhythm, the identity, or the rhythm as well as the identity in the sequence and the feedback was varied. Each condition consisted of a control trial with usual feedback and five experimental trials with delayed feedback from the fifth syllable onwards. Results show an influence of changes in identity on sequence length and voice level, but only in parts an influence of changes in rhythm on the same parameters. In conclusion, displaced rhythm -among other factors- only contributes to the well-known effects of delayed auditory feedback.

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