

## Article

# Changes in Anticipatory VtoV Coarticulation in French during Adulthood

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**Abstract:** In this study, we test whether anticipatory Vowel-to-Vowel coarticulation varies with age in the speech of 246 adult French speakers aged between 20 and 93. The relationship between coarticulation and the known age-related change in speech rate is also investigated. The results show a gradual decrease in the amount of coarticulation for speakers from 20 to mid-50s, followed by a more abrupt decrease for speakers older than 70. For speakers in between, diverse coarticulation profiles emerge. Speech rate is also found to evolve from early to late adulthood and not only for older speakers; it shows a gradual decrease for speakers up to mid-50s and a more abrupt deceleration afterwards. Yet, the relationship between rate and coarticulation is not linear; it appears stronger for the younger speakers, with faster speakers coarticulating more, than for the adults over 70 y.o.a. Results are discussed in relation to possible changes in the parametrization and coordination of speech units at different ages.

**Keywords:** coarticulation; age; aging; French; VtoV anticipatory coarticulation; speech production; speech rate



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## 1. Introduction

Anticipatory coarticulation, i.e., the anticipation of an upcoming sound in speech, has long served to investigate the process of planning and execution of coordinated speech units. Indeed, if a speech unit is anticipated into a preceding one, this implies that both units have been concomitantly planned and sent for execution. In other words, their co-production is a reflection of the fact that the two units are encoded and coordinated in the same speech plan (see Whalen 1990; Kühnert and Nolan 1999; Ma et al. 2015; Recasens 2018).

Studies on children's speech development have shown that coarticulatory patterns change during childhood. This has been reported for anticipatory effects between both adjacent and non-adjacent sounds, although the direction of these changes is not clear. Indeed, studies on anticipatory VtoV coarticulation have shown either a greater or a lesser degree of coarticulation in children than adults. Noiray et al. (2019) found an overall greater degree of coarticulation in children aged 3 to 7 with respect to adults, as well as a decrease in coarticulation with children's increasing age (although the effect depended on the intervening consonant). A similar result, with more coarticulation in children aged 4 to 6 than adults, was also reported by Nijland et al. (2002). On the other hand, Barbier et al. (2020) found less coarticulation in children aged 4 to 10 when compared to young adults. Similar inconsistencies are shown in studies on CV anticipatory coarticulation. Whereas (Zharkova et al. 2012; Zharkova 2017) found less intrasyllabic coarticulation in children aged 6 to 9 than adults, and in children aged 5 compared to adolescents, Nittrouer et al. (1996), conversely, reported greater coarticulation in children aged 3 to 6 than adults.

Taken together, these results suggest that coarticulation within and between the units of speech is not stable during the lifespan, but evolves throughout childhood. Indeed, despite the controversial results, coarticulatory patterns are said to progressively approach

adult ones with increasing age (e.g., [Noiray et al. 2019](#)). In that respect, the adult coarticulation pattern to which children's productions are compared is intended as 'the' reference for a mature speech production system where coarticulation is assumed to be stable. That said, this reference is very often that of quite young adults (for example, under 30 y.o.a. in [Noiray et al. 2019](#); [Barbier et al. 2020](#); around 30–40 y.o.a. in [Zharkova et al. 2012](#)), as is the case of many other studies on which our knowledge of speech production is based.

The main question we aim at addressing in the present study is whether coarticulation is indeed stable in adult speech; and if not, how it varies according to speakers' age. Moreover, we aim at exploring possible causes for this variation.

There are several reasons for speech to evolve during adulthood. These can be linked to physiological or cognitive changes accompanying natural aging, but also to many other changes conditioned by speech usage and life experience. Several age-related speech changes have been documented in the literature (see among others [Fougeron et al. 2021](#)). Of particular interest for our research question are the changes reported on aspects linked to the temporal organization of speech, which could interact with a change in coarticulation patterns.

Before turning to the implications of age-related variations in speech for coarticulation, we will review some of the findings reported in the literature.

Many cross-sectional studies that have explored the effects of aging have shown a deceleration of speech with age. At the sentence level, a slower rate for older speakers has been reported in both spontaneous and read speech, in terms of a decrease in articulation rate ([Ramig 1983](#); [Jacewicz et al. 2009](#)), or an increase in sentence duration ([Bourbon and Hermes 2020](#); [Horton et al. 2010](#)). At the segmental level, older speakers have been found to exhibit longer acoustic durations and longer duration of tongue movements in vowel production ([Albuquerque et al. 2019](#); [Mücke et al. 2021](#)). This deceleration of speech in older speakers has been related to the overall slowing of body movements with age. For instance, finger movements, movements of the tongue and handwriting have also been shown to be slower in older than in younger adults (respectively, [Caçola et al. 2013](#); [Bilodeau-Mercure et al. 2015](#); [Hirai et al. 1991](#); [Rosenblum et al. 2013](#)).

It is of particular interest that these changes do not seem to be specific to old age. For example, the results of [Bilodeau-Mercure et al. \(2015\)](#) support the idea that the slowing down of finger movements occurs quite early (already for the 37–54 years old group). For speech, changes occurring early in adulthood have also been reported. [Jacewicz et al. \(2010\)](#) found an increase in speech rate until the late 40s, and then a decrease for older speakers. Conversely, [Fougeron et al. \(2021\)](#) documented, on a large sample of speakers including some of the speakers who participated in the present study, a continuous decrease in speech rate from 20 to 93 y.o.a., with a sharper slowing down after the mid-50s.

Changes in speech rate and in coarticulation can be related, but their relationship is not straightforward. Coarticulation can be seen as the overlap between speech units that are spatiotemporally defined, that is, have their own internal duration (i.e., gestures in Articulatory Phonology for instance; [Browman and Goldstein 1990, 1992](#)). If so, without changing gestures' duration, an increase in overlap will make gestures "slide" more into one another and thus will reduce the duration of the sequence (among others, [Hardcastle 1985](#); [Byrd and Tan 1996](#)). Presumably, a decrease in overlap would produce the opposite effect, corresponding to a lengthening of sequence duration. In other terms, a change in coarticulation degree could co-occur with a change in the temporal unfolding of speech units and a consequent change in rate. The slow rate of older speakers could thus explain a decrease in coarticulation degree.

Nonetheless, manipulating gestural overlap is not the only way to vary speech rate. Observation of speaker-specific strategies in response to speech rate manipulations shows that the relationship between rate and articulatory coordination and kinematics is rather complex (for a review, see [Berry 2011](#)). Multiple variables are at play: for instance, fast speech can be achieved by increasing overlap between gestures ([Engstrand 1988](#)), by increasing the velocity of the articulators ([Tillmann and Pfitzinger 2003](#)), or by decreasing their displacement ([Goozée et al. 2003](#)).

In studies where intentional changes of speech rate are elicited as part of the protocol, the results do not point toward a single direction as for the effects of rate changes on coarticulation. At a fast rate, an increase in anticipatory coarticulation is generally reported for adjacent sounds for VtoC and CtoV coarticulation and in CC clusters (e.g., [Gay 1981](#); [Agwuele et al. 2008](#); [Hardcastle 1985](#)); but for coarticulation between non-adjacent sounds, such as in VtoV coarticulation, results are less striking. [Recasens \(2015\)](#) found a slight (barely significant) increase in lingual anticipatory coarticulation between /a/ and /i/, as measured by F2, at a fast rate. [Matthies et al. \(2001\)](#) showed an increase of labial coarticulation in /iCu/ sequences at a fast rate, but no effects on lingual coarticulation. Moreover, they reported some individual variability in coarticulation degree. Changes in coarticulation at slow rate have been even less investigated. For adjacent sounds, [Tjaden and Wilding \(2005\)](#) found a decrease in coarticulation at a slow rate on CtoV coarticulation in VC heterosyllabic sequences but not on VtoC coarticulation in tautosyllabic CV sequences. As for non-adjacent sounds, [Hertrich and Ackermann \(1995\)](#) found no effect of a deceleration of speech rate on anticipatory VtoV coarticulation.

Another aspect can be considered regarding the slowing of speech in older speakers. These slower speakers produce longer vowels, for which articulatory targets have more time to be achieved. For example, [Fletcher et al. \(2015\)](#), in a cross-sectional analysis on speakers aged 65 to 90, reported more peripheral vowel targets for speakers who exhibited longer vowel duration. On the other hand, fast younger speakers are supposed to produce shorter vowels, which could come with an undershoot of articulatory targets (if there is no increase in velocity; [Goozée et al. 2003](#)). In their longitudinal study, [Gahl and Baayen \(2019\)](#) showed that from 20 to 50 years of age, vowels for the same speakers tend to get more peripheral, leading to an expansion of the vowel acoustic space. However, this was found for both short and long vowels. This change from more reduced to more peripheral realizations of vowel targets, regardless of vowel duration, suggests that the kinematic organization of speech may also change according to speakers' age. The more peripheral articulation of their middle-aged speakers could indeed result from larger movement displacements and a potential increase in velocity when peripheral targets need to be reached in a reduced time (as is the case for short vowels).

Other studies looking for an age-related change in vowel articulation in much older speakers have shown quite inconsistent results (see [Eichhorn et al. 2018](#), for instance). However, some results also suggest a possible change in the kinematic organization of vowel gestures: a tendency toward a reduction of vowel targets at old age has been suggested in several studies (e.g., [Albuquerque et al. 2019, 2020](#)), even in presence of longer segmental durations ([Liss et al. 1990](#); [Mücke et al. 2021](#)).

In the present study, we will further investigate the relationship between coarticulation and speech rate with the hypothesis that they may covary along adulthood. We expect speech rate to decelerate with age. If a slower rate indeed comes with a decrease in gestural overlap, a reduction of coarticulation for slower, and thus older speakers, is to be expected. However, this relationship does not have to be linear since multiple aspects affecting the kinematic parametrization and coordination of speech units may change with speakers' age.

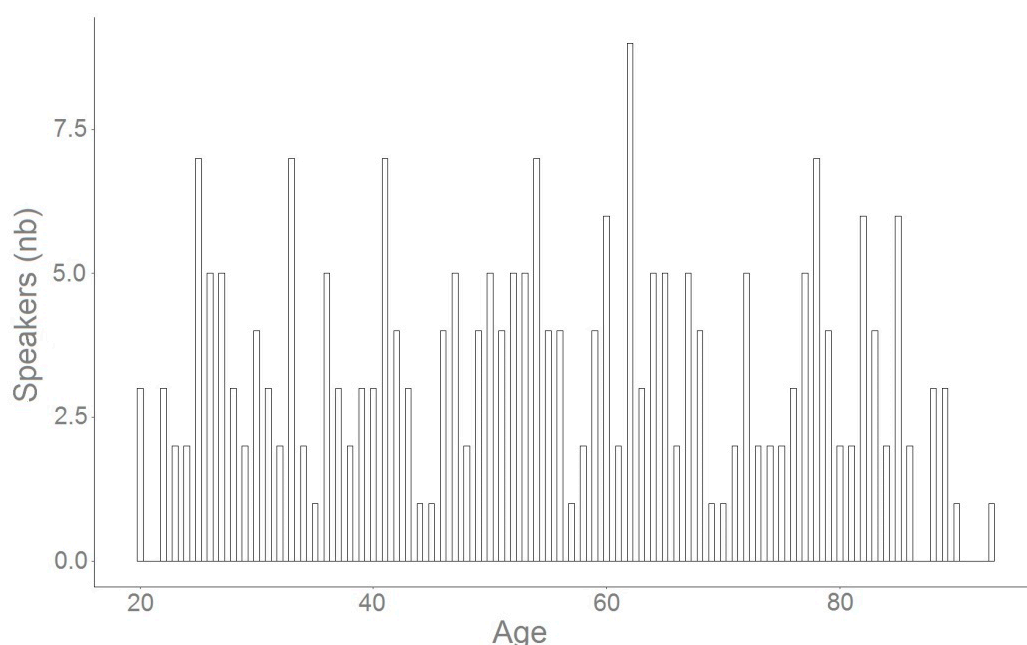
## 2. Materials and Methods

### 2.1. Participants

The productions of 246 healthy native French speakers (123 females and 123 males) spanning from 20 to 93 years of age were selected for this study. The distribution of speakers' age is illustrated in [Figure 1](#). The recordings were selected from existing databases collected in the context of three related projects (the MonPage, MoSpeeDi, and Speech'N'Co projects).

Participants were recorded in three cities of different French-speaking countries: Paris, in France (42 females and 42 males), Geneva, in Switzerland (42 females and 42 males), and Mons, in Belgium (39 females and 39 males). They were all recruited from local

communities in order to have a varied social and educational background in the population, but it was verified that recruitment was balanced across countries.



**Figure 1.** Distribution of the population according to the chronological age of the speakers.

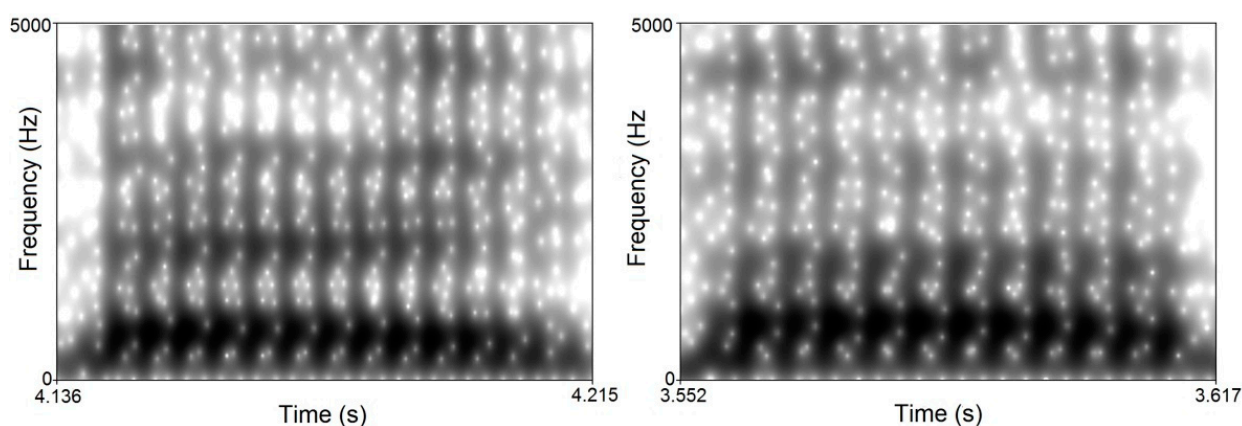
Regional diversity was also meant to introduce diversity in the population, but the inclusion of the participants was not strictly focused on well-defined regional varieties in each location. For example, speakers recorded in Geneva originated mainly from the larger Lemanic area; speakers recorded in Paris originated mainly from diverse regions within the northern half of France. All participants spoke French as their primary language (mother tongue and currently used language).

A subset of this data (127 speakers) was used in a pilot study (D'Alessandro and Fougeron 2018) in order to test for confounds due to differences between French regional varieties. Dialectal differences were found in vowel duration, with participants from Belgium presenting longer vowels than both participants from France and Switzerland, but this regional property did not interact with age. Preliminary analysis on the variation of coarticulation according to age showed that the effect of age was similar in the three regional varieties. We therefore pooled all speakers together for the present study.

## 2.2. Speech Material and Acoustic Analysis

Speech materials consisted of the reading of an isolated sentence and of a short story (188 words), presented in Appendix A. These two tasks are part of the MonPaGe speech screening protocol (Laganaro et al. 2021; Pernon et al. 2020) which was designed to assess the speech of patients with Motor Speech Disorders on several speech and voice dimensions.

Anticipatory VtoV coarticulation is studied on the word /papi/ (*papi*, “grandpa”) who is one of the main characters of the story. Coarticulation is measured as the influence of V2/i/ on V1/a/in/papi/, which translates to a lowering of F1 and a rising of F2, and thus to a decrease in the compacity of the /a/, as exemplified in Figure 2. There were six occurrences of /papi/ per speaker. Notwithstanding, due to reading errors, 18 speakers produced five out of six /papi/ and four produced four out of six, thus a total of 1449 items were analyzed.



**Figure 2.** Spectrogram of /a/ in *papi* (left) compared to the first /a/ in *papa* (right). The compacity between the two formants (F2–F1) of /a/ appears to be reduced in *papi* compared to *papa*: F1 is lower and F2 is higher.

Target vowels /a/ and /i/ in *papi* words were manually segmented. Vowel onset was defined by the beginning of voicing or of the second formant (whichever appeared first), while vowel offset was defined by the end of the second formant. The first two formants of the target vowels were extracted using the Burg algorithm of PRAAT (Boersma and Weenink 2021) with the following settings: detection of five formants between 0 and 5 kHz for males and between 0 and 5.5 kHz for females on a 0.025 window length. The automatically extracted formant values were checked visually in search of outliers and detection errors were manually corrected when needed. Formants values were taken at three different timepoints and then averaged in a single value, in order to minimize detection errors that escaped manual correction. The chosen timepoints depended on the vowel: for V1/a/, formant values were taken at 50%, 60%, and 70% of total vowel duration, i.e., in a portion of the vowel that is most influenced by the following /i/; for V2/i/, formant values were taken at 30%, 40%, and 50% of total vowel duration, in order to avoid the portion of the vowel that could be influenced by the following context, which varied in the text.

In order to be able to pool male and female data in a single analysis and to reduce as much as possible the effect of speaker-specific spectral characteristics, the following procedure was applied. First, the formant values in Hertz were transformed in Bark using the Traunmüller (1990).

Second, a coarticulation index was designed to measure coarticulation token by token with the following formula:

$$\frac{(F2 - F1/a/) - (F2 - F1/i/)}{(F2 - F1/i/)}$$

The index computes how much the /a/ vowel assimilates to the spectral characteristics of the following /i/ within the same token. These characteristics are expressed in terms of the compacity between the first two formants (F2–F1). As illustrated in Figure 1: coarticulation with a following /i/ makes the /a/ less compact, i.e., increase the distance between F1 and F2. The inclusion of F2–F1/i/ in the denominator is meant to account for speaker and token-specific realizations of /i/. A higher value of this coarticulation index means that /a/ is spectrally more similar to /i/, and thus indicates more coarticulation; a lower value means that /a/ stays more spectrally distinct from /i/, and thus indicates less coarticulation.

A measure of speech rate per speaker was computed on the reading of a short sentence (*Melanie vend du lilas*, “Melanie sells lilac”) as part of the MonPaGe screening protocol (Laganaro et al. 2021). The beginning and the end of the sentence were semi-automatically annotated in PRAAT in order to extract total sentence duration. Speech rate was then calculated as the number of expected phonemes over sentence duration. For most speakers, it corresponds to articulation rate, but for speakers who introduce a short pause after the

subject of the sentence, it is a measure of speech rate (since the pause is included in the sentence duration).

### 2.3. Statistical Analysis

Statistical analyses were carried out using Multivariate Adaptive Regression Splines (MARS) models, built with the package *earth* (Milborrow 2021) in the R software (R Core Development Team 2021). MARS modeling is an extension of linear models that can be used to model linear and non-linear relationships between variables. Unlike step functions, the nature of the non-linearity does not need to be assumed in advance. Indeed, the model looks for the first point in the data (knot) where a linear regression between  $x$  and  $y$  can be fitted with the smallest error, creating what is called a hinge function ( $a - 0 \cdot x$ ) or  $(0 \cdot x - a)$ , where 'a' is the knot. It continues searching for these cutpoints until the end. In a second step, the knots that do not contribute significantly to predictive accuracy are eliminated to avoid overfitting. Moreover, it automatically performs variable selection, excluding variables with no explanatory power (in case of collinearity) and assessing variable importance. Variable importance measures the impact of the prediction error as features are included (Friedman 1991; Boehmke and Greenwell 2019).

In order to investigate first the relationship between speech rate and age for our speakers (recall that rate is expected to slow down with aging), we built a MARS model with SPEECH RATE as the dependent variable and AGE as the explanatory variable.

Then, to test whether and how coarticulation covaries with age and speech rate, we built a MARS model with the COARTICULATION INDEX as the dependent variable and AGE and SPEECH RATE, as well as their interaction, as explanatory variables.

Model selection was carried out by performing a  $k$ -fold cross-validation as implemented in the *earth* package, in order to estimate how the model would perform on unseen data and thus avoid overfitting. This method works by splitting the dataset into  $k$  groups, using one group as a test dataset and the rest as training sets. We tuned models' hyperparameters retaining the model that performed better in this procedure.

For each model, as measures of performance estimate, we will present the  $R^2$  and the Cross Validated  $R^2$ , which is the mean of the  $R^2$  calculated for the different models *earth* created during the procedure.

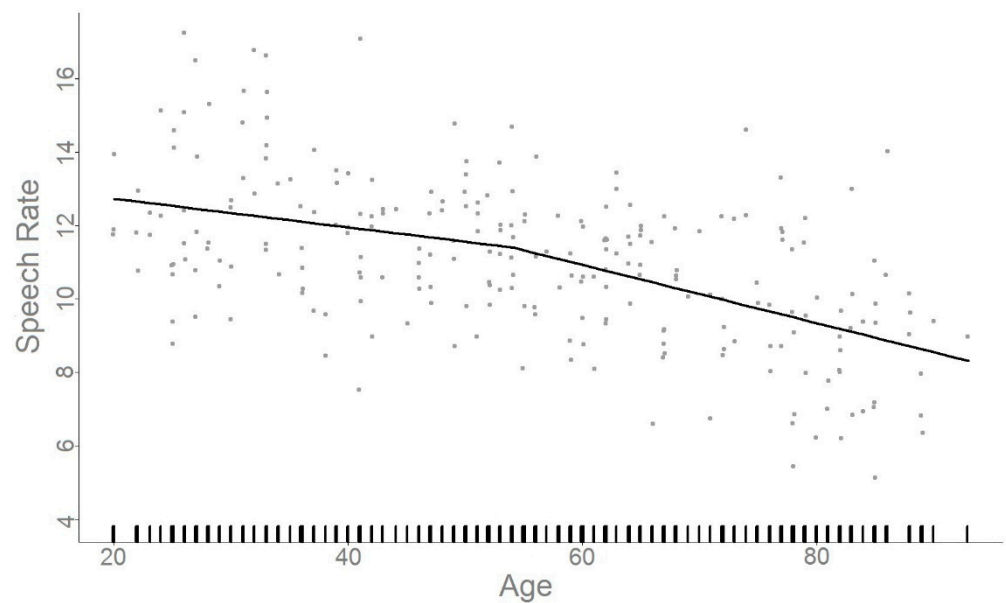
## 3. Results

### 3.1. Relationship between Speech Rate and Age

Figure 3 presents the distribution of the speakers according to their speech rate and their chronological age. It clearly shows that speech rate decreases as speakers' age increases. This trend is continuous from 20 to 93 y.o.a. but a sharper slowing down occurs after middle age. The MARS model finds a knot at age 54, with a steeper decrease for speakers older than 54 ( $\beta = -0.08$ ) than for speakers who are younger ( $\beta = -0.04$ ). As expected though, speakers' age alone explains only a small portion of the variance in speech rate in the population ( $R^2 = 0.29$ ,  $CVR^2 = 0.25$ ).

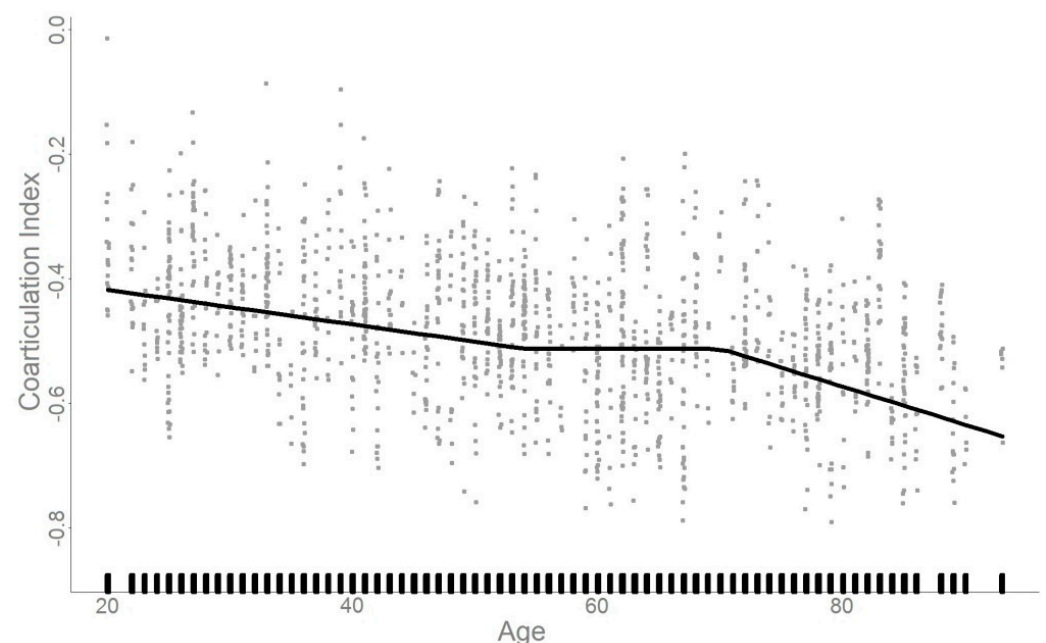
### 3.2. Relationship between Coarticulation, Age and Speech Rate

In the second analysis, we test how AGE and SPEECH RATE predict coarticulation. The MARS model yielded the two covariates AGE and SPEECH RATE. However, the two variables in the interaction explain the COARTICULATION INDEX only moderately ( $R^2 = 0.18$ ,  $CVR^2 = 0.16$ ). AGE is given as the most important predictor, but the two factors are found to interact with each other in a complex but very interesting way. Before turning to the interaction between variables, we will describe how each variable alone covaries with coarticulation.



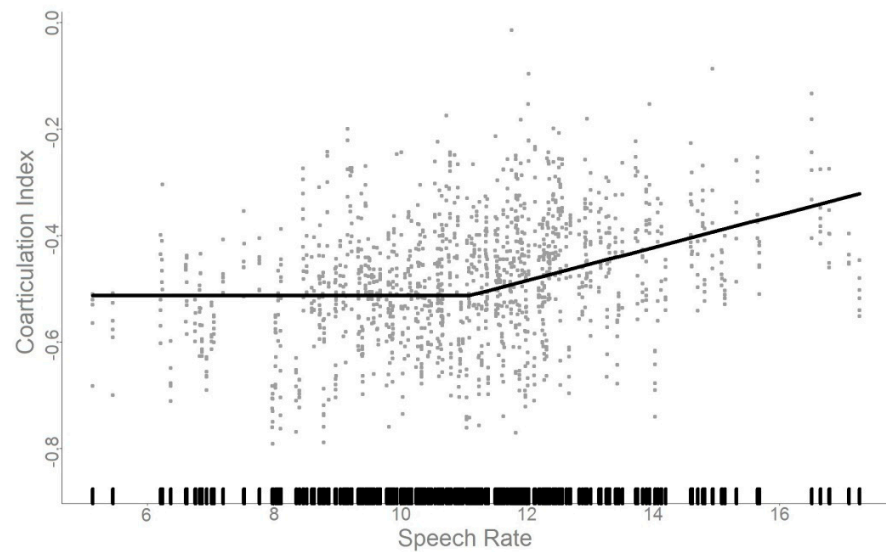
**Figure 3.** Relationship between Age ( $x$ -axis) and Speech Rate in phoneme/s. ( $y$ -axis) per speaker. The dark line represents the hinge functions of the MARS model, with a knot found at age 54.

Figure 4 presents the coarticulation indices computed per token (5–6 per speaker) according to the speakers' age. It appears clearly that coarticulation reduces with an increase in age, but in a non-linear way. Coarticulation decreases smoothly up to a knot at 54 y.o.a. ( $\beta = -0.003$ ) and then more abruptly after 70 y.o.a. ( $\beta = -0.006$ ). Between the knots found at age 54 and 70, there is a large dispersion of coarticulation indices with several interactions, which will be further discussed below.



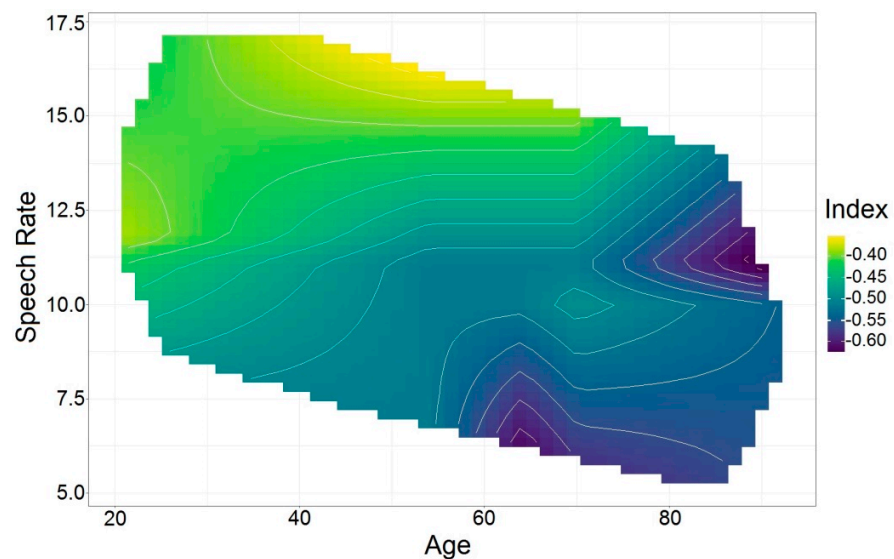
**Figure 4.** Relationship between Age per speaker ( $x$ -axis) and Coarticulation Index per token ( $y$ -axis). The more the Coarticulation Index approaches 0 the more there is coarticulation.

Figure 5 presents the coarticulation indices according to speakers' speech rate. Again, the relationship is non-linear and much less continuous than the one found with age. Indeed, coarticulation is found to increase with speech rate only for rates faster than 11.08 phoneme/s, where a knot is found ( $\beta = 0.03$ ).



**Figure 5.** Relationship between Speech rate per speaker (*x*-axis) and Coarticulation Index per token (*y*-axis).

The interaction between the two predictors AGE and SPEECH RATE and coarticulation is illustrated in Figure 6. As in the previous figures, we see that until around the mid 50s speakers show a large amount of coarticulation (light colors and coarticulation index approaching to 0), which slightly reduces (darker colors) for the speakers with the slowest rates (below about 11 ph/s). For speakers above approximately 70 y.o.a., coarticulation is low (dark colors) and does not seem to depend much on speech rate. Indeed, we can see a small cluster of speakers in the middle right part of the figure which shows a very small coarticulation index and a rate around 11 ph/s, while other speakers with a lower rate have a slightly bigger coarticulation index. Above 70 y.o.a., coarticulation seems to increase with rate only for the ones who speak the fastest (e.g., above 13 ph/s). Nevertheless, for these older speakers, coarticulation is lower than that of younger speakers at the same rate. In the middle part of the figure, for speakers between 54 and 70 y.o.a., we find a wide range of speech rates and a clear covariation between rate and coarticulation: the slower the speaker speaks, the less coarticulation is found. In particular, a very low coarticulation index is shown by speakers who present a rate lower than 10 ph/s.



**Figure 6.** Interaction between Age (*x*-axis) and Speech Rate (*y*-axis) in the prediction of Coarticulation Index (in color: the more the coarticulation index approaches 0 (lighter colors), the more there is coarticulation).



#### 4. Discussion

In this study, we investigated whether anticipatory Vowel-to-Vowel coarticulation evolves during adulthood and whether such a change could be related to a deceleration of speech rate with age in adult speech.

The first outcome of this study concerns the effect of age on speech rate. As expected, speech rate is found to decrease with age. As found in [Fougeron et al. \(2021\)](#) on a larger population that includes the 246 speakers studied here, speech rate presents a continuous decrease with increasing age. In the two studies, the decrease in speech rate is also found to be steeper for speakers after middle age. The knots found by the MARS models used are largely dependent on the population on which the analysis is done, however, it is interesting that they differ only slightly (here 54 y.o.a. vs. 57 y.o.a. in the other study) while speech rate is measured on a quite different material (the reading of a sentence here vs. several sentences in a text in the other study).

The novel outcome of our study relates to the finding that coarticulation also evolves with age in adult speech: the amount of anticipatory VtoV coarticulation is found to decrease with age in our population. As measured by our coarticulation index, coarticulation corresponded to the amount of acoustic assimilation of V1 to V2 in /papi/. We found a reduction of this index with age, meaning that /a/ stays acoustically more distinct from /i/ for the older speakers, who therefore coarticulate to a lesser extent.

Another notable finding of this study is that the decrease of coarticulation degree according to the age of our speakers is not linear. Three stages can be roughly identified. Coarticulation decreases gradually with age for speakers between 20 and middle-age, and then drops steeply with age for speakers older than 70. For speakers in between (50s–60s), we find a large diversity of coarticulation indices, which could be either due to speakers' and/or tokens' specific patterns.

The question at hand is: why does coarticulation decrease with age? Several interpretations are possible. The first one relates to the co-occurrence between a decrease in speech rate and a reduction of coarticulation with age. The coarticulation index we derive from the acoustic signal can be tentatively interpreted in terms of gestural overlap: a high coarticulation index captures a strong acoustic assimilation between /a/ and /i/ in /papi/, which in turn reflects the blending of the two coproduced vowel gestures. A slower speech rate can reflect the increase in the duration of the individual gestures, but also a reduction of their overlap, hence their blending. In other terms, a reduction of coarticulation and a reduction of speech rate could be the two sides of the same coin.

Notwithstanding, this interpretation stands mostly for speakers under 50 years of age. As a matter of fact, if coarticulation and speech rate tendentially covary, this relationship is not the same at all ages. Until the mid 50s, speakers present generally higher speech rates and there is a strong covariation of rate and coarticulation, with faster speakers (faster than a “threshold” rate found at about 12 ph/s.) coarticulating more than their slower peers. For these speakers, variation in the coordination between speech unit and their degree of overlap seems to be prominent for distinguishing speakers with different rates. From the mid 50s to 70 y.o.a, speech rate overall lowers, and speakers present a wide range of coarticulation profiles, from low to high coarticulation degrees. For these speakers, coarticulation also covaries with rate, but the threshold rate over which coarticulation approaches that of younger speakers is set higher (around 14 ph/s). At rates lower than this threshold, middle-aged speakers always present overall less coarticulation than younger ones at the same rate. A more substantial change in the relationship between rate and coarticulation is observable for speakers older than 70. They show a globally lower coarticulation degree, rates lower than 14 ph/s. and, crucially, no variation in the degree of coarticulation according to rate, except for the (few) very fastest ones.

In light of these results, explaining a change in coarticulation solely by a change in rate (or vice versa) does not hold at all ages, and other accounts need to be discussed.

Let's turn first to the middle aged speakers that coarticulate less than younger speakers who present the same rate. This difference in coarticulatory behavior could be related to

speech/reading style. As a matter of fact, we are doing a cross-sectional comparison of speakers of different ages, and therefore we cannot disentangle speaker-specific, generation-specific, and language changes from age effects. Older speakers may present a more careful and emphatic reading style than younger adults. Similar to ‘clear’ or ‘communicative’ speech, this reading style could imply less coarticulation, as found in other studies looking at anticipatory coarticulation in different speech styles (Duez 1992; Scarborough and Zellou 2013). These speakers could implement a different strategy than younger speakers, by increasing velocity in order to reach speech targets in less time for instance, in order to preserve a clearer speech (cfr Van Son and Pols 1992). A tendency for hyperarticulated speech targets from speakers in their 50s is also suggested by Gahl and Baayen (2019), who showed in a longitudinal study that middle-aged speakers produced more peripheral targets compared to when they were younger, and this hyperarticulation is found even for short vowels when the time to reach the target is little.

To some extent, a more hyperarticulated reading style could also explain the weak covariation of rate and coarticulation in speakers above 70 y.o.a. A tendency toward a more careful and hyperarticulated speech for older speakers is supported by the results of Mücke et al. (2020), on the production of CCV syllables in German by speakers aged 70 to 80 and younger speakers. Older speakers showed a more symmetrical organization of the consonants of the cluster and the vowel, which suggests a tendency to hyperarticulate. In a study on the effects of the rate increase on coarticulation and articulatory precision (D’Alessandro et al. 2020), we found that when speakers are asked to produce fast repetitions of syllables, younger (<40 y.o.a.) and older speakers (>68 y.o.a.) adopt different strategies. While younger speakers achieved a fast rate by reducing articulatory precision and increasing coarticulation, older speakers increased repetition rate (with the same acceleration ratio as younger speakers) without changing coarticulation or articulatory precision. These results suggest that older speakers may have a bias toward increasing articulatory effort in order to maintain “clearer” speech, but also that the rate they reach, even for fast repetitions, may not be fast enough to require more overlap between gestures.

Speech change with age should also be considered in connection with other age-related changes, especially at old age. Above approximately 70 y.o.a., the fast and coarticulated speech profiles that we have observed for younger speakers almost totally disappear. Overall, the speech rate drops under about 13–14 ph/s. and the degree of coarticulation is low. Some old speakers present a very slow speech rate, probably due to the presence of a pause in their sentences, but others have a similar speech rate to that of younger speakers, yet with much less coarticulation. This is particularly striking for the rates between 10 and 12 ph./s. on the right part of Figure 3, where the reduction in the coarticulation index is clearly a function of age in the pool of speakers between 70 and 93 y.o.a.

A decline in the ability to plan and control movements in old age has been documented in the literature. For instance, in a handwriting task, Rosenblum et al. (2013) reported that older adults require more time to plan the next phase of the movement and show decreased hand movement fluency with respect to younger adults. Older adults (70–80 y.o.a) have also been shown to exhibit asymmetrical tongue movements in vowel production, with shorter acceleration phases and longer deceleration phases (Hermes et al. 2018). Longer deceleration phases suggest that older adults slow down the movement approaching the target to make more corrective adjustments in order to gain accuracy in presence of difficulties in the control of movements (Ketcham and Stelmach 2004). This is also supported by studies that show more adjustments in the trajectory of older adults’ arm and hand movements with respect to younger adults (Cooke et al. 1989; Pohl et al. 1996).

Such a decline in the control of speech movements could explain the slowing down of speech gestures and thus the decrease in speech rate. It could also explain a reduction of coarticulation (independent of rate) if it induces a disruption in the coordination between the speech units under consideration here. As said earlier, in order to be coarticulated, the /a/ and /i/ in ‘papi’ need to be somehow coordinated together, as well as coordinated with the elements of their own syllable (here the onset/p/s). Trans-consonantal VtoV

coarticulation has been shown to vary according to the language (see review in Manuel 1999) or the syllabic affiliation of the intervocalic consonant (Mok 2012). It is thus coherent to assume that the trans-consonantal link between the vowels, and thus the way their articulatory specifications interact with each other, is controlled. A reduction in coarticulation at old age could then be associated with a reorganization of the coupling between the trans-consonant vowels. For instance, a planning of speech on smaller units, syllable by syllable, similar to walking with small steps, could be a careful and efficient strategy for older speakers in order to maintain speech accuracy and fluency in the presence of difficulties in the control of movements.

To conclude, coarticulation and speech rate, as well as their relationship, continuously change across the lifespan. The fact that coarticulatory patterns evolve with age has been documented for children by previous literature. Here, we provided new results showing that they still evolve during adulthood, and not only in old age. These results warn us of the risks of using a restricted age group as a reference for adult speech, in studies on childhood development but also in studies on pathological speech. Further research is needed to better understand how changes in coarticulation with age are part of a more global change in the way we speak. However, the low variance in coarticulation explained by age and rate in our data also suggests that many more factors need to be explored in order to understand individual patterns of coarticulation.

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## Appendix A

### Speech Material

1. *Melanie vend du lilas*
2. *Lundi, le chat, le loup et Papa vont à Bali. Les copains sont tout contents. Mardi, Papi y va aussi. Il dit: “Je n’ai pas un sou! Qui va prendre soin de moi?” “Moi!” dit le chat, “moi!” dit le loup. “Vous?” Papi réfléchit. Mercredi, Papi dit: “Toi, le chat, tu es doux, tu es chou, tu n’as pas de poux! Mais pas ce loup: il a une cape rouge et je n’aime pas ce gars-là!”. Jeudi, le chat et Papi se baladent à Bali. Papa glisse! Aie! Ouille! Son cou craque, son coude claque, c’est la débâcle!. Vendredi, Papa a mal. Il pleure, il crie! “Toi, Papi, aide-moi, trouve le nain!” “Un nain? On n’en a jamais vu par ici?!”. Samedi matin, le chat va voir son ami le loup et lui dit: “Aide-moi à soigner Papa!”. Samedi soir, le loup lui donne sa recette magique: “Coupe un oignon, cache-le sous la souche, et lorsque le lilas fleurira, Papa sera guéri!” Abracadabra, ça y est, on a réussi!. Dimanche, le chat tout doux, le loup magicien, Papa et Papi quittent Bali. Les copains sont tout contents.*

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