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Abstract

Research suggests that synchronization between musicians during ensemble performances can be affected by the rhythmic or tonal complexity of the piece being performed and by group roles such as leader-follower relationships. Since previous studies have mostly been conducted within single performance sessions, developmental aspects of interpersonal synchronization in ensembles remain under-investigated. This longitudinal study followed a newly formed singing ensemble from initial rehearsals to the performance stage, to investigate the evolution of synchronization between advanced singing students during their first term of study, in relation to the musical content of the piece and leader-follower relationships. An advanced post-graduate singing quintet was recorded using head-worn microphones and laryngograph electrodes to allow fundamental frequency evaluation of the individual voices. The quintet, formed to complete a one-year Masters programme in ensemble singing, rehearsed two pieces composed for the study, during five rehearsals over three months. Singers practised the same pieces in a randomised order across rehearsals and performed three repetitions of the same pieces before and after each rehearsal, resulting in 6 recordings per piece/rehearsal. Audio and laryngograph data of the repeated performances were collected, and synchronization was measured by extracting note times from the fundamental frequency values. The averaged asynchronies of the two pieces before and after rehearsals were calculated and compared both within rehearsals (pre- and post-) and between rehearsals (rehearsals 1 to 5). Results demonstrate an increase in the precision of synchronization over the course of study, depending on the piece being rehearsed, and a more variable synchronization for the more rhythmically complex piece. Results also show changes in the distribution of the tendency to precede all co-performers across rehearsals, which became equally distributed among the musicians during the last rehearsal. The results reported here could have important implications for the tailoring of rehearsal strategies that could improve interpersonal synchronization between musicians during ensemble performances.

Keywords	interpersonal synchronization; rehearsal stages; entrainment; ensemble communication; joint action.

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Submission Files Included in this PDF

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Research data have been uploaded to Zenodo, and will be linked to the DOI when this will be available.

York, June 24 2018

Journal of Voice Editorial Office
The Voice Foundation
219 N. Broad Street, 10th Floor,
Philadelphia. PA 19107

Dear Sir/Madam,

I hereby submit the jointly revisited manuscript for consideration for publication in the Journal of Voice, *A longitudinal study investigating synchronization in a singing quintet*.

A summary of this work has been accepted for presentation at The Voice Foundation's 47th Annual Symposium: Care of the Professional Voice.

Looking forward to hearing back from you,

Best wishes,

Sara D'Amario

BIO

SARA D'AMARIO is currently a doctoral researcher at the University of York, investigating interpersonal interactions between co-performers in music ensemble. She earned degrees in Piano Performance, Chamber Music, and Musicology at the Conservatory of Music of Milan (Italy). She also obtained an MA in Psychology of Music at the University of Sheffield (UK). Sara has +30 years of international experience as pianist, piano teacher, and music educator.

Helena Daffern is currently a Lecturer in Music Technology in the Department of Electronic Engineering at the University of York. She received a BA (Hons.) degree in music, an M.A. degree in music, and the D.Phil. degree in music technology, all from the University of York, UK, in 2004, 2005, and 2009, respectively, before completing training as a classical singer at Trinity College of Music. Her research utilises interdisciplinary approaches to investigate voice science and acoustics, particularly singing performance, vocal pedagogy, choral singing and singing for health and wellbeing.

Dr Freya Bailes is a University Academic Fellow at the University of Leeds, working in the area of Music Psychology. Prior appointments include Lecturer in Music at the University of Hull (2012-15), and Senior Research Fellow at the MARCS Institute at the University of Western Sydney, where she collaborated with Professor Roger Dean on research into the perception and emotional expression of contemporary music, and the role of leadership in musical improvisation. This research drew on her previous post-doctoral experience at the L.E.A.D. (Université de Bourgogne), the C.S.M.L. (Ohio State University), and the Sonic Communications Research Group (University of Canberra).

Title:
A longitudinal study investigating synchronization in a singing quintet

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Point-by-point responses to reviewers' comments

A Longitudinal Study Investigating Synchronization in a Singing Quintet

Reviewer 1:

Review for J Voice of
A Longitudinal Study Investigating Synchronization in a Singing Quintet

Overall: There are a comments that are from the singers after the last rehearsal relating to all rehearsals and I find these rather vague and memory reliant (it is a month after the last rehearsal if I have understood properly). You state there are observational data and I would want to see some of this used to substantiate these comments about leadership etc. As it stands, the paper is weakened by the lack of reliable qualitative data. Authors' reply: This paper is a quantitative study of the interpersonal synchronization between singers, measured objectively through acoustics and electrolaryngography recordings. The questionnaire data were collected at the end of the last rehearsal, retrospectively in relation to the previous rehearsals, and were note supposed to be the focus of the manuscript. We agree that these qualitative data are not fully reliable, as we also stated in the discussion. Considering the reviewer's comments, the section in the results including the comments collected through the questionnaire has been deleted. Similarly, any comments about singers' perception of synchronization have been deleted from the Discussion.

The thorough analysis of the verbal interactions among singers during rehearsals is out of the scope of the paper; it is conducted by a different led researcher and will be reported elsewhere. In the present paper, verbal discussions have been scrutinized in relation to clear reference to synchronization (See Method/Design last paragraph, "*As far as the current study, the verbal discussions were scrutinized in relation to singers' specific reference to synchronization, and the results reported in the introductive section of the results*"), and the results reported in the first section of the Results, and debated in the last paragraph of the Discussion ("*the improvements in the synchronization observed across rehearsals are not linked to any specific targeted practise of the singers to improve synchronization, as demonstrated by the lack of specific reference to synchronization in the verbal discussions during the five rehearsals*"). Singers never referred to synchronization during the five rehearsals, therefore the changes/improvements observed across the five rehearsals are not related to specific strategies or discussions used by the singers during the five rehearsals.
Eventually, the paper firmly centres on the measured synchronization in line with research in this field of research (see among the others, Goebl & Palmer, 2009; Timmers et al 2013. 2014; Keller & Appel, 2010; Bishop & Goebl, 2015). Then, it further expands the knowledge of coordination in music ensemble observing the developmental aspects of synchronization in singing ensemble, an area that was never investigated before, to the best of our knowledge.

L9-10: Seems a little odd that 'advanced singing students' are in their *first* term of study – please reword. Authors' reply: This has been reworded as "between advanced singing students during a university term of study"

L10: remove comma after 'study' - Authors' reply: this has been done as track change

L50: Using 'remarkably precise' suggests some absolute value of precision – what would it be? Surely it is all relative depending on what is being considered and therefore should be stated relative to some non-precise/precise action time? Author's reply: This has been reworded as "Their joint action is remarkably precise, as shown by the typical asynchrony measured between …".

L71: What are these pulses that are mentioned in the context of the paper? What does 'mostly intentional' mean in the context of singing; indeed what would unintentional mean in the singing context? Authors' reply: pulses refers to the musical beat (added to the manuscript as follows:" two or more different consecutive beats are aligned"). This section of the paper refers to the framework applicable across musical ensembles and therefore applies to singing as it would any instrumental group. The beginning of the paragraph has been amended to clarify this: "These incessant temporal adaptations, which enable such remarkable sensorimotor synchronization in any musical ensemble, are sustained by two independent error correction processes, named phase correction and period correction[8]". In addition, "mostly intentional" has been amended in the paper as "Period correction, by contrast, refers to the controlled adjustments of the duration of each timekeeper interval on the basis of previous information; it is not automatic but requires conscious and explicit attention, control and awareness by …".

L80: Explain 'corrective gain' in this context. Authors' reply: "researchers found that the first violinists exhibit contrasting patterns of adjustments with the co-performers. In one quartet, the first violinist showed fewer adjustments to the co-performers, than the others' adjustment to her. In the second quartet, researchers found no difference in the adjustment patterns between the first violinist and the other members of the ensemble. These findings suggest different strategies used during the performance, i.e. first-violin led vs a more democratic approach".

L131: Why a singing quintet when quartets are rather more common for singing groups – does this not add a further degree of freedom? Author's reply: this has been clarified in the manuscript as follows: "The analysis of interpersonal synchronization has been mostly conducted investigating duo[12,13,18–22] and quartet performances[14–17]. This study focuses on singing quintet performances, an area that currently lacks thorough investigation"

L139: Spelling: 'practice' not 'practie'. Author's reply: This has been modified.

L144: Is there a reference for the ethical approval? Author's reply: Yes, it's D'Amario070817. This has been added in Method/Participants.

L152: Please define 'formal singing practice'. Author's reply: The reference to "practice" was a mistake; the authors intended to refer to "training". The phrase has been slightly reworded as follows "All singers had formal singing training with a professional singing teacher ($Mdn = 8, Range = 13$)". The Median and Range values have been reported rather than Mean and SD, since this small sample size was not normally distributed.

L152: Presumably their 5 years' experience performing in a singing ensemble was not in the same ensemble (since they had met for only one rehearsal) – please make clear what these separate experiences were (solos, duets, trios, quartets etc.) and whether there was any other relevant musical experience such as conducting, composing or choir singing. Author's reply: Indeed, they previously performed in singing ensembles, but this was the first performing together in this ensemble. The manuscript has been amended as follows: "All singers had formal singing training with a professional singing teacher ($Mdn = 8, Range = 13$), and extensive experience performing in choir ($Mdn = 10.8, Range = 11$) and in singing ensembles such as duo, trio and quartet ($Mdn = 5, Range = 8$). The bass had 12 years of experience conducting, and 5 years composing."

L152: This suggests that each singer had ensemble experience (5 years) that was not formal singing practice (3 years) – I am not clear what this means. Author's reply: they had at least 5 years of experience working on ensemble, and at least 3 years of formal singing training. All singers had several years of experience singing in church choirs.

L154: There should be some indication as to whether the tinnitus could be an intrusive factor for this work. Authors' reply: this has been clarified as follows: "who reported sporadic tinnitus during his life that never affected singing during the rehearsal sessions"

L156: Which chorales were they, why were they selected and why was it not possible to use quintet compositions? Author's reply: This has been clarified in Methods/Material. "This investigation made use of two chorales composed by Johann Sebastian Bach: one piece was the chorale "Jes, mein Hort und Erretter" from the Cantata BWV 154 "Mein liebster Jesus ist verloren"; the other was the chorale "Nun danket alle gott" from the Cantata BWV 192. These chorales were chosen for their structural characteristics: two short pieces, mostly homophonic, with different melodic contour and harmonic structure, and feasible to be mastered during five, short rehearsal sessions […] To facilitate the analysis of synchronization based on f_o tracking (see 2.6 Analysis), the two pieces were arranged based on the following criteria: i) avoiding repeated notes, and ii) limiting semitones. The melody of each part avoids repeated notes and includes very few semitones in order. Synchronization can be potentially difficult to compute from the f_o track of audio recordings when melodies move chromatically, since the expected *vibrato* range for classical singers might span a semitone. Similarly, true beginnings of repeated notes during *legato* singing can be difficult to detect, if singers do not produce a noticeable pause in phonation between notes. Two pieces with these characteristics (i.e., without repeated notes, and only few semitones), which maximize asynchrony detection were difficult to find, and arrangement of the pieces was preferred".

L158: Why was the vowel /i:/ selected (arguably the vowel /a:/ might be more natural to run a tune through to)? Author's reply: In a previous study (D'Amario et al, 2018) subjects chose /i/ and this has been kept for consistency across the studies. This aspects has been added to the manuscript as follows: "This vowel was chosen by the singers that took part to a pilot study investigating synchronization in singing duo performances[22]. The same vowel was used in the present study for consistency with the previous investigation" (see Method/Materials)

L160: It is not clear that a wide vibrato (was this actually evidenced in the performances?) would disrupt f0 tracking; more importantly could be identifying note onsets with a wide vibrato which is more relevant to this study. Author's reply: A wide vibrato was sometimes present in the recordings, and its impact on the onset detection based on the *fo* tracking has been reworded as following: "Synchronization can be potentially difficult to compute from the f_o track of audio recordings when melodies move chromatically, since the expected *vibrato* range for classical singers might span a semitone."

L169: I am not familiar with '1:1 note ratio' – I would assume it means equal note lengths in each chord - perhaps a brief explanation could be added? - Author's reply: this has been clarified as follows "with a constant 1:1 note ratio across performers (i.e., equal note length between each voice), featuring .."

L192: Indicating absorptive acoustic material in the room is interesting but it does not betray its acoustic characteristics – what about noise from outside the room and its reverberation which could affect synchrony? How far apart were the singers? How large was the room – was it more like a performance or practice space? Was there an audience? Were the singer in a line facing as if (or to) an audience, or perhaps in a ring singing more to each other? I would suggest that all of these could affect synchrony. Author's reply: The room characteristics have been explained in the paper as follows: "The experiment took place in a bespoke recording studio of the Department of Electronic Engineering at the University of York. The room was $(5.2m \times 7.6m)$, the ambient noise level was 37dB(A), and the RT60 reverberation time was 0.32s. Therefore, the room was an environment not alien to the singers in terms of acoustic (relatively dead typical of a practice room or recording studio) and look (a recording studio with acoustic panelling on the walls and recording equipment) – see Method/Apparatus. There wasn't an audience (this has been added to Methods/Procedure last paragraph). They stood in semi-circle in the order S1-S5 at 1.5 m from the stereo mic placed pointing at S3 (this has been clarified Method/Apparatus).

L198: If the stereo microphone was around 1.5m from the lips, this suggests that the singers much have been placed on a circle around the microphone for them all to be at the same distance – I assume it was an omnidirectional microphone (I do not know the NT4 characteristics off hand)? This should be discussed in the context of published work on singer spacing in choirs. Author's reply: clarified in the manuscript as follows "The quintet stood in a semi-circle of approximately 1.5m radius in the sequence soprano (S1), mezzo 1 (S2), mezzo 2 (S3), tenor (S4) and bass (S5), with S1 opposite S5 [...] The stereo microphone used in the study was a twin cardioid microphone pointing towards S3, with its main axes pointing at S2 and S4. This stereo microphone was chosen as being most sensitive to the area in front to the microphone capsule, where the singers stood, while picking up minimal noise from the rear and marginal from the sides [...] This ensemble was not a choir with several voices per part, but a vocal ensemble. This aspect limits the relevance of any comparisons to spacing in choirs. Nevertheless, some considerations have been made regarding the placement of voices. The 1.5 m radius was chosen so the distance between adjacent singers was $2\pi*1.5/(2*4) \approx 1.2$ m. This is larger than a conventional choral spacing, but close to what is often considered preferable on a concert podium[18]. In combination with the fact that each singer was

alone per part, this distance of 1.2 m indicates that the self-to-other ratio was high, and that each singer could very easily hear their own voice above the others".

Lines 203 and 206: Surely there are 12 outputs (not 11)? Author's reply: Yes! This has been modified.

L217: This sounds like an intensive rehearsal schedule – were singers fully engaged throughout? Author's reply: Yes, they were. This has been specified in the manuscript (see Methods/Procedure 1st paragraph).

L218: A month after the last rehearsal seems rather late for an interview relating to a 15 week activity – wouldn't details be fading? Why was the questionnaire only administered after the final rehearsal and not after each rehearsal? Author's reply: The questionnaire was administered only at the end of the final rehearsal, rather than after each rehearsal, to avoid the singers discovering the purpose of the study, which was to observe what emerges spontaneously in terms of synchronization. For this reason, asking at the end of rehearsal 1, for example, might spoil rehearsal 2. But, we agree that the questionnaire data are not reliable, and have been removed from the manuscript.

L237: Here I see they stood in a semicircle – something is not right since if at 2m diameter the microphone could not be 1.5m from the lips of each singer! Authors' reply: This has been corrected. They were in a semicircle of 1.5m in radius with the stereo mic placed at approximately 1.5m from the lips

L260: I am not clear why pitch errors are excluded since this study is not about pitch? Authors' reply: This decision was not made over the "pitch" value (I,e, average *f*o values). "Note errors due to the singers missing notes or performing the wrong notes (i.e., entering or delaying the notes for more than 50% of its expected values) were less than 0.05%, identified comparing Lx and audio recordings with the notated scores. Notes at which errors occurred were excluded from the analysis"

L285: Justify the selected value for p (0.016) here. Authors' reply: This has been clarified as follows: "A Bonferroni correction was implemented for multiple multilevel linear models, dividing the critical *p* value (0.05) by the number of comparisons being made, three, corresponding to the total number of models developed for the three response variables. For this reason, a p-value threshold was set at $p = 0.016$.

L322: Justify the selected value for p (0.0045) here. Authors' reply: This has been clarified as follows: A Bonferroni correction was carried out for multiple chi-square tests, which were 11 in the study. A p-value threshold was set at $p = 0.0045$, obtained dividing the critical value (0.05) by the number of chi-square tests (i.e., $p = 0.05/11$).

L393-395: Relating to my comment above for L218 I do wonder how reliable these self-reported synchronisation values were following a month's delay. Authors' reply: Self-reported synchronization values have been removed.

L404-409: Was there any external observation of the group that might have spotted any leading – individuals might think they are leading or being led but what confidence can one place in such subjective judgements? Authors' reply: comments related to subjective judgments of leadership have been removed from the paper. A full analysis of leadership among singers during rehearsals is currently under investigation by a different led researcher, and will be reported elsewhere, as leadership conceptualized as social role is out of the scope of the present paper.

L422: While it does suggest this is related to complexity of the piece it could also be related to their inability to hear asynchrony in their singing – I would like to see an external judgement based on the recordings as to how synchronous they became after rehearsal 2 and whether there was scope to improve further or not (in the view of the expert). What does 'stable degree of synchronization' mean; it is a crucial comment in this regard that suggests they could not improve further (which I doubt). How synchronous was piece B after the five rehearsals? Authors' reply: Indeed, it would be useful for future investigation to analyse the perception of synchronization from a pool of experts and also non-experts and examine the relationships between the objectively measure synchronization and its perception. This would be a very interesting, stand alone study, recommendable for future research, but it is out of the scope of the paper. This has been stated in the manuscript in Limitations and future work as follows: "Precision of synchronization improved between the first two rehearsals in piece A, and improved consistently in piece B across the term of study. It is now of interest to investigate whether this improvement is perceivable. A listening test including multiple recordings of the same pieces for each rehearsal is planned, analysing whether the performers, other musicians and non-experts might perceive a change in the degree of synchronization".

L430: Can a figure be put on 'consistency' of synchronisation or is it a subjective judgement? Authors' reply: That is not a subjective judgement. Consistency was quantified by SD (standard deviation) of absolute asynchronies (as explained in 2.6 Method/Analysis, 5th paragraph). Then a multilinear mixed model was implemented on such SD asynchronies and the results presented in 3.2 Results/Consistency, which also included a figure (see Fig 5). To remind the reader in the discussion that consistency was measured objectively, this has been now clarified in the Discussion as follows: "Synchronization in piece A was more consistent than piece B in each rehearsal, as quantified by the SD of absolute asynchronies"

L432: As for L430 – how was 'consistency improved significantly' judged in practice? Authors' reply: That was done through a post-hoc test that was reported in 3.2 Results/Consistency/last paragraph, stating "In addition, post-hoc comparisons between rehearsals of the two pieces show that the consistency of piece improved significantly from the first rehearsal (?? = 81.9, ???? = 122.0) to the second rehearsal (?? = 47.4,?? = 66.9,?? = 9.3,?? < 0.001), as shown in Figure 5B"

L435: I am not convinced that simply 'preceding other voices' is an indication of leadership – I guess it is in part down to how you define leadership in this context which should be included. For example, were there any body movements that could be construed as conducting; something that is often observed in my experience when a singer thinks a piece should be faster/slower or more together? Authors' reply: We also agree that

preceeding/lagging is a limited way to test leadership, and this was stated in the introduction, specifying that it is a common way, but does not provide the full picture. The intro stated: “Overall, the results from the above studies analysing leadership in ensemble playing demonstrate that lagging behind or preceding a co-performer might be related to their leader-follower roles. Therefore, the analysis of preceding or lagging a co-performer during ensemble performance is a valuable measure of leadership, which is usually thought of in a social context, rather than in terms of performance timings”. Then in the discussion, this was restated as following “Although the analysis of the rank order positions does not offer a thorough analysis of the leader-follower relationships, these results suggest that the tendency to precede all co-performers changes across rehearsals, becoming equally distributed among singers toward the end of a first-term of study”. In addition, in the conclusion, the results about leader-follower have been reported in terms of tendency to precede/lag, rather than leading/following (see Conclusion/end of first paragraph, “Finally, the tendency for members of the ensemble to precede/lag the others differed significantly across rehearsals, suggesting that leader-follower relationships changed in different rehearsals. The tendency to precede all co-performers became equally shared among the 5 singers by the last rehearsal session”). The focus of the study is on synchronization (precision and consistency) and leader-follower roles (conceptualized in terms of tendency to precede-lag, in line with previous investigations – see Goebl & Palmer 2009, Zamm et al 2015). The analysis of body movements would definitely provide useful information and could be an interesting study in itself, however is outside the scope of the present paper.

L436: What aspects were you observing in coming to the conclusion that 'no significant differences between the members of the quintet were apparent with respect to leading'? Authors’ reply: This was based on the analysis of leadership as quantified by entering in position 1 as explained in Results/Tendency to precede/lag/3rd paragraph stating “Notably, there was no significant difference between singers in occupying the first position in rehearsal 5 ($\chi^2(4) = 6.389, p = 0.172$).” The sentence 'no significant differences between the members of the quintet were apparent with respect to leading' has been slightly reworded to clarify this aspect, as follows:” Analyses show that while singers varied in the balance of leadership (as indexed by preceding all other voices) across the first four rehearsals, by the final rehearsal no significant differences between the members of the quintet were apparent in occupying the first position.”

L439: What is the evidence for stating that the 'leader-follower relationships .. fluctuate over time, stabilizing toward the end of a first-term of study'? Authors’ reply: This was based on the 5 goodness of fit chi-square tests reported in Results/Tendency … 3rd paragraph, stating “Results from the goodness of fit chi-square test indicate that the observed frequencies of position 1 for each singer (see Figure 7) were not equally distributed across rehearsal 1(??2(4) = 69.022,?? < 0.001), rehearsal 2(??2(4) = 17.392, ?? = 0.002), rehearsal 3 (??2(4) = 53.094,?? < 0.001), and rehearsal 4 (??2(4) = 27.572,
?? < 0.001). Notably, there was no significant difference between singers in occupying the first position in rehearsal 5 (??2(4) = 6.389,?? = 0.172).” Nevertheless, the sentence “'leader-follower relationships .. fluctuate over time, stabilizing toward the end of a first-term of study”, has been slightly reworded as follows: “Although the analysis of the rank order positions does not offer a thorough analysis of the leader-follower relationships, these

results suggest that the tendency to precede all co-performers changes across rehearsals, becoming equally distributed among singers toward the end of a first-term of study"

L453: Might the reports of the singers about improvements across the term of study be buried in the detail of the data you have gathered in terms of perhaps more subtle interactions between individual parts that do not have any noticeable impact on the overall summary statistics observed? Might there be some way of teasing this out since the singers seem to be stating it? To suggest that the singers might have difficulty recalling details (as I have suggested above about reliability of that recall) suggests a flaw in the experimental design. Authors' reply: the questionnaire has been removed.

L470: As singers were told to focus on expressiveness, was any analysis done of this? Why might their focus then be temporal synchronisation as a rehearsal goal – again I wonder whether there was any observation made of individual rehearsals to explore what they were focussing on – I note that there is data (L483) on this which should be called on to reinforce statements about what was being worked on in each rehearsal. Authors' reply: No analysis has been done on expressiveness, as this is a bit out the scope of the paper (i.e., synchronization that emerges spontaneously during 5 rehearsal sessions across 4 months). Verbal discussions have been now investigated in relation to synchronization, and this has been added to the manuscript as explained above (singers never made explicit reference to synchronization issues during the five rehearsals). The thorough analysis of the verbal interactions (i.e., in relation to leadership as social roles, rehearsal strategies implemented, singers initiating and following, etc…) will be a parallel investigation, which will occupy an entire paper, and this is out of the scope of the paper.

Reviewer 2

Very interesting article. Some comments and suggestions follow:

146: Not clear here with "quintet" and "3 females" and is the mean and SD relate to the females or the whole group. Do you mean "… of which 3 were female"? Authors' reply: Yes! "of which" has been added to the manuscript to clarify this

151: Did the singers "each" have 3 years of formal singing practice? All the same? No other experience (e.g. school choir, church choir?). Authors' reply: The reference to "practice" was a mistake; the authors intended to refer to "training". Each singer had "at least" 3 years, with one having 3 years and other more than three. We acknowledge that this was confusing. The phrase has been slightly reworded as follows "All singers had formal singing training, i.e. with a professional singing teacher, ($Mdn = 8$, $Range = 13$). " The Median and Range values have been reported rather than Mean and SD, since this small sample size was not normally distributed.

154: Did you consider the tinnitus an issue, or not. Either way, justify your decision. Authors' reply: this has been clarified as follows: "who reported sporadic tinnitus during his life that did not affect singing during the rehearsal sessions"

196: The head microphones "were placed on the cheek of the singer" - two microphones on one cheek? Authors' reply: Only one head-mounted microphone was placed on the check of the singer! This has been clarified in the manuscript as follows "Each head-mounted microphone was placed on the cheek of each singer"

199: Nice, if brief, description here of Lx and when/why it is used. But no description of why the different microphones were used. Or how that results in "two sets of data" and not 4. Authors' reply: added in Methods/Apparatus in track-changes as follows "The Lx signal may be too weak to be reliable for use on certain populations, such as sopranos[20] and when a thick layer of subcutaneous tissue is present in the neck[21]. The Lx recordings resulted to be unusable for 0.7% of a set of 96 recordings of a short two-part piece composed for a singing duet, and discontinuous Lx segments in the order of 30ms were observed in a study testing the use of laryngograph for the analysis of synchronization in singing ensembles. [19] Close proximity microphones were used to investigate synchronization when the Lx signal was unusable. The stereo recordings were collected for future investigations of the verbal interactions between singers, but were not used for the analysis of interpersonal synchronization." The number of data sets collected has been corrected to 4 (see Methods/Apparatus), though the data sets extracted for the analysis of synchronization were only 2 (see Methods/Analysis), since the stereo mic was not used, as stated in Methods/Apparatus.

225: Unclear if the singers were accompanied (e.g. by piano) during any part of the rehearsal and, more importantly, during the recordings Authors' reply: This has been clarified in the manuscript as shown in 2.5 Methods/Procedure at the end of the last paragraph. "Singers performed and rehearsed the pieces a cappella, and a piano was not used during the five rehearsals."

238: This sentence is unclear: "Singers were required to work on expressiveness, pretending to work towards a final performance of the stimulus pieces at the end of the term of study; this was designed to challenge the singers during rehearsals" - why "pretending" and why was there a design need to "challenge" the singers? Authors' reply: This has been clarified in the manuscript as shown in 2.5 Methods/Procedure: "This was designed to encourage a realistic approach to rehearsal and promote a development of the quintet, although the two pieces rehearsed in the laboratory sessions were not performed on stage at the end of the study term"

251: Typo, should be "input" not "inputted". Authors' reply: Changed to 'then entered into Excel' for ease of reading

247: Were the f0 estimates taken from the audio or Lx signal? If the audio signal, how was the f0 extracted given that the acoustic voice data of the other singers would also be present? Authors' reply: the detection of onsets/offsets/note beginning/note endings mostly relied on the Lx signal. Nevertheless, *f*o estimates from the acoustics data were scrutinized in cases of a weak Lx signal, or soft phonation. See Methods/Analysis

263: Typo, should be "focused" not "focussed". Authors' reply: "focussed" is kept as reference to the UK English tradition. American English, which would use "focus", is not a mandatory requirement for Journal of Voice; and the authors decided to use British English.

A Longitudinal Study Investigating Synchronization in a Singing Quintet

Research suggests that synchronization between musicians during ensemble performances can be affected by the rhythmic or tonal complexity of the piece being performed and by group roles such as leader-follower relationships. Since previous studies have mostly been conducted within single performance sessions, developmental aspects of interpersonal synchronization in ensembles remain under-investigated. This longitudinal study followed a newly formed singing ensemble from initial rehearsals to the performance stage, to investigate the evolution of synchronization between advanced singing students during a university term of study in relation to the musical content of the piece and leader-follower relationships.

An advanced post-graduate singing quintet was recorded using head-worn microphones and laryngograph electrodes to allow fundamental frequency evaluation of the individual voices. The quintet, formed to complete a one-year Masters programme in ensemble singing, rehearsed two pieces composed for the study, during five rehearsals over three months. Singers practised the same pieces in a randomised order across rehearsals and performed three repetitions of the same pieces before and after each rehearsal, resulting in 6 recordings per piece/rehearsal. Audio and laryngograph data of the repeated performances were collected, and synchronization was measured by extracting note times from the fundamental frequency values. The asynchronies of the two pieces before and after rehearsals were calculated and compared both within rehearsals (pre- and post-) and between rehearsals (rehearsals 1 to 5).

Results demonstrate an increase in the precision of synchronization over the course of study, depending on the piece being rehearsed, and a more variable synchronization for the more rhythmically complex piece. Results also show changes in the distribution of the tendency to precede all co-performers across rehearsals, which became equally distributed among the musicians during the last rehearsal. The results reported here could have important implications for the tailoring of rehearsal strategies that could improve interpersonal synchronization between musicians during ensemble performances.

Keywords: interpersonal synchronization, rehearsal stages, entrainment, ensemble communication

A Longitudinal Study Investigating Sensorimotor Synchronization in a Singing Quintet

1 Introduction

Sensorimotor synchronization refers to the interpersonal synchronization of rhythmic movement with an external rhythm [1,2]. This ubiquitous behaviour occurs in many contexts, such as hand shaking, playing sports, music, and dancing. It was previously thought to be unique to humans[1], however, it was recently observed in some animals. A dancing bird, named Snowball, and a California sea-lion were able to synchronize head bobs with a beat of a Backstreet Boys song[3] or a metronome[4], respectively. In some activities, interpersonal coordination emerges spontaneously, for example when people rocking chairs or walking together adjust their movements or stride[5]. Sometimes, coordination of movements occurs even when people intentionally try not to coordinate their actions, if visual information between them is shared[6]. In other contexts, synchronization is intentional, being based on a specific goal, such as during music ensemble performances.

Notably, in ensemble playing sensorimotor synchronization represents an essential skill. Musicians in small ensembles must coordinate their actions with their co-performer's actions, and orchestral members must follow the conductor's gestures in order to achieve performance excellence. Their joint action is remarkably precise, as shown by the typical asynchrony measured between nominally synchronous sound events being in the order of 30-50ms in small ensembles[7].

A theoretical framework has been proposed including three cognitive processes that enable this tight interpersonal coordination in ensemble performances, named i) *anticipatory auditory imagery,* ii) *prioritized integrative attention,* and iii) *adapting to others' action timing*[8]. The first process, *anticipatory auditory imagery,* refers to the ability to anticipate one's own sound and the co-performer sound, creating auditory and motor imagery of their auditory effects; this auditory imagery ability depends on the level of musical experience[9]. The second process, *prioritized integrative attention*, refers to an attentional strategy that musicians employ to facilitate cohesive and precise performance. Musicians pay attention to their own actions and to the co-performers' actions, whilst assessing the overall incoming actual sound from the ensemble. The third process, *adapting to others' action timing*, is an important ability in ensemble performance, and refers to the constant temporal adjustment of one's own timing with the co-performer(s)' timing. Temporal adjustments are necessary to master intentional expressive tempo changes or unintentional temporal fluctuations due to noise in the cognitive motor processes.

These incessant temporal adaptations, which enable such remarkable sensorimotor synchronization in any musical ensemble, are sustained by two independent error correction processes, named phase correction and period correction[8]. Phase correction refers to the automatic process that adjusts the way two or more consecutive beats are aligned, and thus greatly supports precision in interpersonal synchronization. Period correction, by contrast, refers to the controlled adjustments of the duration of each timekeeper interval on the basis of previous information; it is not automatic but requires conscious and explicit attention, control and awareness by the musicians[10,11]. Period correction is mostly needed with obvious tempo change, whilst phase correction is continuously triggered to adapt to small temporal fluctuations. Phase and period corrections appear gradually, rather than instantaneously, after a timing change is introduced in the synchronization or a joint action begins.

Findings regarding error correction processes are mostly based on tapping tasks, in which participants tap along to rhythmic sequences of auditory stimuli (for a review, see[1,2]). Recently, they have also been investigated in two professional string quartets. In this case, researchers found that the first violinists exhibit contrasting patterns of adjustments with the co-performers. In one quartet, the first violinist showed fewer adjustments to the co-performers, than the others' adjustment to her. In the second quartet, researchers found no difference in the adjustment patterns between the first violinist and the other members of the ensemble. These findings suggest different strategies used during the performance, i.e. first-violin led vs a more democratic approach[12].

Reported evidence indicates that synchronization in ensembles could be affected by the rhythmical complexity of the piece being performed[13–15]. The modality of sensory information occurring between beats was investigated in a study manipulating the number of notes within each crotchet beat. Pianists performing melodies with a metronome were less synchronized when playing melodies in which the crotchet beats were subdivided by adding quaver notes, compared with when the crotchets beats of the melodies were not subdivided[13]. In addition, pianists performing duets with different note ratios between the two musical parts (1:1, 1:2, and 2:1 ratio) were best synchronized when the lower part was playing fewer notes (2:1 ratio) and less synchronized when playing more notes (1:2 ratio), under conditions whereby the upper parts heard only themselves whilst the lower parts heard both parts[14]. Pianists were also more synchronized when playing the same melody in unison than in a round, characterized by a delay of the entry of the second performer, suggesting that the non-simultaneous entrance might decrease the degree of synchronization[15]. The effect of the rhythmical complexity of the piece has not been analysed in larger ensembles; further investigations might shed some light on the effects of the rhythmical complexity of the piece on the sensorimotor synchronization between musicians in larger ensembles.

Temporal coordination can also be affected by the role of the individuals within a group, such as leader-follower relationships between musicians in ensembles. Investigations based on duo performances, in which specific group roles were assigned between musicians, demonstrate that the effect of acting as leader or follower might affect synchronization in ensembles, depending on the piece being performed[14–17]. The designated leader is more likely to precede the co-performer in melody-accompaniment pieces[14], to lag when performing the same melody in a round[15], but not to be affected by the instruction to act as leader or follower when playing a two-part piece with a less clear separation of roles induced by the score[17].

A number of case studies have recently analysed leadership in string quartets, which emerges spontaneously during performances, without assigning specific group roles[18–21]. The analysis of temporal coordination and/or body movements among musicians indicates the relative leadership of the first Violin[20], and a complex pattern of leader-follower relationships during ensemble performances[18,19]. These findings contrast with a simpler division of roles characterized by the artistic attribution of leader to the first Violin, with co-performers acting as co-leaders/followers. Another study forced the unidirectional communication between the first Violin of a string quartet and the other members of the ensemble, by introducing changes to the score being performed known only to the first Violin. Notably, when dynamic and temporal changes were introduced to the score, the unidirectional relationship with the first Violin decreased, suggesting that leadership in ensembles might be affected by the sharing of knowledge between co-performers[21].

Overall, the results from the above studies analysing leadership in ensemble playing demonstrate that lagging behind or preceding a co-performer might be related to their leader-follower roles. Therefore, the analysis of preceding or lagging a co-performer during ensemble performance is a valuable measure of leadership, which is usually thought of in a social context, rather than in terms of performance timings. Research so far has been mostly focused on instrumental ensembles; future investigations with singers are needed to understand better this complex phenomenon in singing ensembles.

Additionally, whilst there is a strong body of research into interpersonal synchronization which analyses single performance sessions, the developmental aspects of synchronization in ensembles remains mostly unexplored. Whilst members of professional ensembles synchronize their entrances with near-perfect precision with the other co-performer(s), this may require practice over several rehearsals to be achieved. Therefore, the investigation of the evolution of temporal coordination between musicians across rehearsals is of interest to music pedagogy, aimed at refining rehearsal strategies, and music psychology and psychology research, in terms of understanding social interaction.

The analysis of interpersonal synchronization has been mostly conducted investigating duo[14–17,22–25] and quartet performances[18–21]. This study focuses on singing quintet performances, an area that currently lacks thorough investigation, and aims to analyse the evolution of sensorimotor synchronization with practice, variation of leader-follower relationships between singers during and across rehearsal sessions, and in relation to the piece being performed. Specifically, this investigation addresses the following questions:

- Do interpersonal synchronization and/or the leader-follower relationships between singers change with practice in a singing quintet?
- Do these changes, if any, differ in relation to the contrasting musical features of the pieces rehearsed?

Although this is an explorative study, it was hypothesized that practice increases sensorimotor synchronization between singers during singing quintet performances, and that this effect depends on the rhythmical complexity of the piece being performed.

2 Method

2.1 Participants

Ethical approval for the study (with reference D'Amario070817) was obtained from the Physical Sciences Ethics Committee (PSEC) at the University of York (UK). A soprano, mezzo, mezzo, tenor, and bass singing quintet took part in the study (of which 3 females, age $Mdn = 23,\ Range = 6$). Singers were Master of Arts students in ensemble singing at the Department of Music of the University of York. At the time of the study, the quintet was a newly formed ensemble established as a regular quintet working towards performances and Masters exams. They had met for only one rehearsal prior to the beginning of the first session, but rehearsed regularly throughout the duration of the study in preparation for their final exam. All singers had formal singing training with a professional singing teacher ($Mdn = 8, Range = 13$), and extensive experience performing in choir ($Mdn = 10.8, Range = 11$) and in singing ensembles such as duo, trio and quartet ($Mdn = 7, Range = 8$). The bass had 12 years of experience conducting, and 5 years composing. They reported not having absolute pitch, and having normal hearing, except for the bass who reported sporadic tinnitus during his life that did not affect his singing during the rehearsal sessions.

2.2 Materials

This investigation made use of two chorales composed by Johann Sebastian Bach: one piece was the chorale "Jes, mein Hort und Erretter" from the Cantata BWV 154 "Mein liebster Jesus ist verloren"; the other was the chorale "Nun danket alle gott" from the Cantata BWV 192. The pieces were arranged for the singing quintet ensemble in the study by the first author. These chorales were chosen for their structural characteristics: two short pieces, mostly homophonic, with different melodic contour and harmonic structure from each other, and feasible for mastery within five, short rehearsal sessions. The two arranged pieces comprise 8 phrases, to be sung *legato* to the vowel */i/*. This vowel was chosen by the singers that took part to a pilot study investigating synchronization in singing duo performances[16]. The same vowel was used in the present study for consistency with the previous investigation. To facilitate the analysis of synchronization based on f_o tracking (see 2.6 Analysis), the two pieces were arranged based on the following criteria: i) avoiding repeated notes, and ii) limiting semitones. The onset-offset detection and, consequently, interpersonal synchronization can be potentially difficult to compute from the f_o track of audio recordings when melodies move chromatically, since the expected *vibrato* range for classical singers might span a semitone. Similarly, true beginnings of repeated notes during *legato* singing can be difficult to detect, if singers do not produce a noticeable pause in phonation between notes. Two pieces with these characteristics (i.e., without repeated notes, and only few semitones), which maximize asynchrony detection were difficult to find, and arrangement of the pieces was preferred. The pieces do not include any expressive markings, as singers were invited to develop their own expressive interpretation. No clear leader-follower roles are defined in the pieces to allow relationships between singers to emerge spontaneously during rehearsals. The two pieces varied in their rhythmic, melodic and harmonic structure, as follows:

- Piece A: characterized by a clear homophonic structure, with a constant 1:1 note ratio across performers (i.e., equal note length for each voice), featuring simultaneous entries and breaths, and a stable rhythm, as shown in Figure 1.
- Piece B: characterized by a different harmonic structure, and a different and more complex melodic and rhythmic structure, including ornamentations within each part that varied the note ratio across performers. Entries were systematically manipulated in a way that, except for the first simultaneous entry, each singer had one occasion to start the phrase on an up-beat ahead of the others (i.e., the mezzo entered ahead of the others in bar 3, the tenor entered earlier in bar 5, the bass in bar 7, the soprano in bar 9, and the mezzo in bar 11), as shown in Figure 2.

The contrasting characteristics identified above were introduced to investigate whether the evolution of synchronization might vary depending on the properties of the piece being sung.

< Figure 1 about here >

< Figure 2 about here >

2.3 Design

This investigation is a longitudinal study including 5 studio-based rehearsals. During each rehearsal, the above pieces were practised, and three repeated performances of the pieces were recorded pre- and post-practice. This study resulted in a 5 (rehearsals) x 2 (pieces) x 2 (takes, 1 pre- and 1 post-practice) x 3 (repeated performances for each take) design, featuring a total of 30 repeated performances per piece, recorded during the course of the study. The order of recording and rehearsing the two pieces was randomized within rehearsals. Therefore, in rehearsal 1, 4 and 5, singers first recorded-rehearsed-recorded piece A, then

piece B; but, in rehearsal 2 and 3, the quintet recorded-rehearsed-recorded piece B first, followed by piece A.

Additionally, a short questionnaire was administered at the end of the last rehearsal, and singers were interviewed a month after the end of the experiment as part of a study into the verbal interactions of the group by a different lead researcher, which will be thoroughly reported elsewhere. As far as the current study, the verbal discussions were scrutinized in relation to singers' specific reference to synchronization, and the results reported in the introductive section of the results.

2.4 Apparatus

The experiment took place in a bespoke recording studio of the Department of Electronic Engineering at the University of York. The room was $5.2m \times 7.6m$, the ambient noise level was 37dB(A), and the RT60 reverberation time was 0.32s. Therefore, the room was an environment not alien to the singers in terms of acoustic (relatively dead typical of a practice room or recording studio) and look (a recording studio with acoustic panelling on the walls and recording equipment). The quintet stood in a semi-circle of approximately 1.5m in radius in the sequence soprano (S1), mezzo 1 (S2), mezzo 2 (S3), tenor (S4) and bass (S5), with S1 opposite S5. This ensemble was not a choir with several voices per part, but a vocal ensemble. This aspect limits the relevance of any comparisons to spacing in choirs. Nevertheless, some considerations have been made regarding the placement of voices. The 1.5 m radius was chosen so the distance between adjacent singers was $2\pi*1.5/(2*4) \approx 1.2$ m. This is larger than a conventional choral spacing, but close to what is often considered preferable on a concert podium[26]. In combination with the fact that each singer was alone per part, this distance of 1.2m indicates that the self-to-other ratio was high, and that each singer could very easily hear their own voice above the others. Four sets of data were acquired: acoustic data, based on head-mounted close proximity microphones (DPA 4065) and a stereo condenser microphone (Rode NT4) providing right and left outputs; and, electrolaryngograph recordings, using electrolaryngograph electrodes (Lx) from Laryngograph Ltd. (www.laryngograph.com). The stereo microphone used in the study was a twin cardioid microphone pointing towards S3, with its main axes pointing at S2 and S4. This stereo microphone was chosen as being most sensitive to the area in front to the microphone capsule, where the singers stood, while picking up minimal noise from the rear and marginal from the sides. Each head-mounted microphone was placed on the cheek of the singer at approximately 2.5cm from the lips, whilst the stereo microphone was placed at equal distance in front of the singers at approximately 1.5m from the lips. Lx electrodes were placed on either side of the neck at the level of the larynx. Lx is widely used for the analysis of the singing voice [27] and has been recently used to investigate synchronization in singing ensemble performances[16,17], as it allows the identification of the individual contribution of each singer. The Lx signal may be too weak to be reliable for use on certain populations, such as sopranos[28] and when a thick layer of subcutaneous tissue is present in the neck.[29] The Lx recordings resulted to be unusable for 0.7% of a set of 96 recordings of a short two-part piece composed for a singing duet, and discontinuous Lx segments in the order of 30ms were observed in a study testing the use of laryngograph for the analysis of synchronization in singing ensembles[16]. Closed proximity microphones were used to investigate synchronization when the Lx signal was unusable. The stereo recordings were collected for the analysis of the verbal interactions between singers during the five rehearsals, but were not used to measure interpersonal synchronization during the repeated performances. Each Lx box was connected to a preamplifier (ART CleanBox Pro) to reduce noise and interference between the Lx boxes

over long cable runs. The 12 outputs (5 Lx with preamplifiers, 5 head-mounted microphones, and the stereo microphone comprising right and left channels) were attached to a multi-channel audio interface (Focusrite Liquid Saffire 56), which was connected to a PC; the 12 outputs were then recorded using a digital audio workstation (Reaper 5.40) at a sampling frequency of 44.1kHz and 24-bit depth.

2.5 Procedure

Ensemble members were invited to five rehearsal sessions over a four-month period, from September 2017 to January 2018. In each session, they rehearsed each piece for 10 minutes, and performed the pieces three times before and after each rehearsal, endeavouring to make each repetition an individual performance. Each session was approximately 1-hour long. Singers were fully engaged during all rehearsals. Prior to the first rehearsal, participants were asked to fill in a background questionnaire and consent form. The first four rehearsal sessions were approximately 3 weeks apart from each other. The fifth session took place after 6 weeks from the fourth, due to the Christmas break. The last rehearsal session was held the week before the ensemble members' formal performance exam, set up in the form of a public concert; this was designed to conclude the analysis of synchronization at a time when the ensemble should be at its most cohesive, since based on four months of practice. Singers were not aware of the purpose of the study. Singers were required to work on expressiveness, working towards a final performance of the stimulus pieces at the end of the term of study. This was designed to encourage a realistic approach to rehearsal and promote a development of the quintet, although the two pieces rehearsed were not performed on stage at the end of the study term. They were left free to use the short rehearsal sessions in any way they chose to create an expressive interpretation. Singers received the score of the stimuli on the day of each lab session to practise and perform the piece, but the first author retained the score at the end of each sessions, so singers were not able to rehearse the pieces between lab sessions. This allowed the authors to record and analyse any changes in the development of synchronization during the term of study. Singers performed and rehearsed the pieces *a cappella*, and an audience was never present.

2.6 Analysis

Lx and audio recordings from the head-mounted microphones were imported in Praat [30] as .wav files, and two sets of data were extracted from each recording: the f_o estimates in Hertz and the corresponding timestamps with a time step of 1 millisecond. These two data sets were then entered into Excel as a tabular list of data. An automated peak-picking algorithm, TIMEX[16], was used to extract the following four time categories, as defined in D'Amario et al.[16]: onsets (ON) and offsets (OF) of phonation, and note beginnings (NB) and note endings (NE) within the sung *legato* phrases from the acoustic and Lx recordings. This algorithm, tested on a set of singing duo recordings, proved to be a valuable and successful method, recommended for the analysis of interpersonal synchronization between singers during ensemble performances[16]. The algorithm relies mostly on the Lx recordings, but automatically scrutinizes the acoustics data from the head-mounted microphones when the Lx signal is too weak to be detected. The acoustic recordings were also scrutinized in case of soft phonation, since the Lx signal may not pick small vocal fold vibrations. The data extraction automated through TIMEX was then visually cross-validated by the first author. Note errors due to the singers missing notes or performing the wrong notes (i.e., entering or delaying the notes for more than 50% of its expected values) were less than 0.05%, identified comparing Lx and audio recordings with the notated scores. Notes at which errors occurred were excluded from the analysis.

All notes from piece A, the clearly homophonic piece, were selected for the investigation of interpersonal synchronization. Conversely, the analysis of temporal coordination in piece B was focussed on notes being relevant to synchronization, as shown in Figure 2.

Asynchronies were then calculated for each pair of singers, subtracting the timing of one singer from that of another, such as soprano minus mezzo, and soprano minus tenor. This procedure gave a matrix with a total of 20 channels of asynchronies. These channels were implemented for each time category (i.e., ON, NB, NE, and OF) selected for the analysis of interpersonal synchronization.

Asynchronies that fell outside 3 times the interquartile range (IQR) were automatically detected as extreme outliers in SPSS (IBM SPSS Statistics v. 24) and excluded from the analysis. The identification of outliers was run for each time category, pre- and post-rehearsal condition, piece and rehearsal.

Three measures of synchronization were used. They were: i) precision of synchronization, as quantified by absolute asynchronies; ii) consistency of synchronization, as quantified by SD of absolute asynchronies, computed across the 20 channels for each time category; and iii) tendency to precede or lag a co-performer, as quantified by signed asynchronies.

Multilevel linear models were then implemented step by step for each response variable (i.e., precision, consistency, and tendency to precede/lag), to investigate the fixed effects of rehearsal sessions and piece (the last one nested within rehearsals), and the random effects of participant, note, time category, and take (i.e., pre- and post-rehearsal), as shown in Tab 1. Pairs of singers were also entered as random effects in the model investigating the tendency to precede/lag. Multilevel linear models were chosen because they reinforce the statistical power of the analysis providing an assessment of the variability of the fixed effects across random effects[31]. The models were implemented in R Studio[32], using the lme4 package. A Bonferroni correction was implemented for multiple multilevel linear models, dividing the critical p value (0.05) by the number of comparisons being made, three, corresponding to the total number of models developed for the three response variables. For this reason, a p-value threshold was set at $p = 0.016$.

In addition, the tendency to precede/lag a co-performer was investigated analysing the temporal rank order across the five singers for each time category/note/repeated performance/rehearsal. As shown in Figure 3, the temporal rank order for note beginnings and onsets was analysed identifying the entrance temporal position of each singer from position 1 (singer who preceded all co-performers), to position 2 (singer who entered immediately after), to position 3, 4, up to position 5 (singer who lagged all co-performers). Similarly, the sequence for note ending and offset was based on the analysis of the exit temporal position.

< Figure 3 about here >

For each singer, the tendency to occupy a given position was measured counting the number of occurrences spent in that position, i.e. the observed frequency on a given position. This was computed for each position/rehearsal/singer, taking all notes, time categories and both pieces together. Then, three aspects of the effect of rehearsals on the tendency to precede/lag were analysed:

- The interaction between rehearsal (1-5) and position (1-5) for each singer, through Pearson's chi-square tests for independence. The test indicates whether the

frequencies observed in each position are independent from the rehearsals. A total of 5 Pearson's chi-square tests were conducted, one for each singer.

- The interaction between rehearsals (1-5) and the frequencies at which each singer sang in position 1, through a Pearson's chi square test for independence. This analysis demonstrates whether there is a significant relationship between rehearsals and the number of occurrences each singer spent in position 1. One chi-square test was implemented, including the frequencies that each singer occurred in position 1 in each rehearsal.
- The distribution of the tendency to precede all the others computed across the five singers for each rehearsal. This investigation was conducted through a total of 5 chi-square goodness of fit tests (i.e., one for each rehearsal), comparing the observed frequency distribution with an equal frequency distribution. These analyses informed whether the tendency to precede all co-performers was equally distributed in each rehearsal. Whilst the previous Pearson's chi square test for independence presented in the previous point is an omnibus analysis that investigates the interaction between rehearsals and frequencies in position 1 across the 5 rehearsals, the 5 chi-square goodness of fit tests allows to narrow the analysis, investigating the distribution separately at each research.

A Bonferroni correction was carried out for multiple chi-square tests, which were 11 in the study. A p-value threshold was set at $p = 0.0045$, obtained by dividing the critical value (0.05) by the number of chi-square tests (i.e., $p = 0.05/11$).

3 Results

The following three sections (see 3.1-3.3) present the results of the analyses of the fixed effects of rehearsal and piece on interpersonal synchronization. The β - fixed effect coefficients - of rehearsal and piece on the predictor being considered (i.e., precision, consistency, and tendency to precede/lag) are given below and in Table 1 with reference to the specific base level of the factor, i.e. rehearsal 2, 3, 4 and 5 *versus* the base level rehearsal 1, and piece B *versus* piece A. The β coefficient indicates that for each 1 unit increase in the predictor being considered, the effect of the given predictor changes by the amount specified by the β coefficient.

In addition, the verbal discussions were scrutinized in relation to specific reference to synchronization, and singers never discussed nor debated synchronization during the five rehearsal sessions.

3.1 Precision

Results from the multilevel linear modelling as explained in Analysis 2.6 show that precision of synchronization improved from the first to the last rehearsals. As shown in Figure 4A and Table 1, compared to the baseline in rehearsal 1, precision improved in rehearsal 2 ($\beta = -9.7, t(40505) = -5.4, p < 0.001$); in rehearsal 3 ($\beta = -6.7, t(40505) = -3.8, p < 0.001$); and also in rehearsal 4 ($\beta = -8.8, t(40505) = -4.9, p < 0.001$) and rehearsal 5 ($\beta = -11.9, t(40505) = -6.6, p < 0.001$). Precision in the synchronization of piece A was better than that of piece B in all rehearsal sessions, as shown in Table 1 and Figure 4B. The variance partition coefficient (VPC) among pairs of singers, time categories and pre- and post-rehearsal was 0.009, 0.030, and 0.00026. This indicates that only 0.9%, 3% and 0.026% of the variability of precision of synchronization over 5 rehearsals can be attributed to pairs of singers, time categories and pre- and post-rehearsal, respectively. As shown in Figure 4B, post hoc comparisons revealed that precision in the synchronization of

piece A improved in rehearsal 2 ($M = 49.2, SD = 43.4$) compared with rehearsal 1 ($M = 58.7, SD = 50.1, t = 6.4, p < 0.001$). Similarly, precision in piece B was better across rehearsals, as it improved in rehearsal 2 ($M = 80.0, SD = 140.1$) compared with rehearsal 1 ($M = 106.9, SD = 50.1, t = 11.6, p < 0.001$), in rehearsal 4 ($M = 71.8, SD = 116.3$) compared with rehearsal 3 ($M = 81.5, SD = 130.1, t = 4.0, p < 0.001$), and in rehearsal 5 ($M = 62.0, SD = 90.5$) compared with rehearsal 4 ($t = 3.9, p < 0.01$).

< Figure 4 about here >

3.2 Consistency

The 5 rehearsals did not predict synchronization consistency, as shown in Figure 5A, but the pieces within each rehearsal were significant predictors. The consistency in the synchronization of piece A was better than that of piece B in all rehearsals, as shown in Table 1 and Figure 5B. The variance partition coefficient between pre- and post-rehearsal was 0.04%, among time categories 5.6%, and among notes 12.5%. In addition, post-hoc comparisons between rehearsals of the two pieces show that the consistency of piece B improved significantly from the first rehearsal ($M = 81.9, SD = 122.0$) to the second rehearsal ($M = 47.4, SD = 66.9, t = 9.3, p < 0.001$), as shown in Figure 5B.

< Figure 5 about here >

3.3 Tendency to precede/lag

Rehearsal number did not predict the tendency to precede or lag a co-performer computed for each pair of singers. The piece being rehearsed predicted the tendency to precede/lag during the first rehearsal: the amount of leadership/lagging was greater when singers performed piece B ($M = 12.4, SD = 198.1$), than piece A ($M = 6.3, SD = 76.9$), $\beta = 10.2, t(39783) = 4.0, p < 0.001$. The VRP among pairs was 0.9%, notes 0.3%, time categories 3.7%, and rehearsals 0.075%.

In addition, Pearson's chi-square tests for each singer which analysed the interaction between rehearsal number and positions in each rehearsal session (as defined in 2.6 Methods/Analysis) show that there was a significant association between the given variables. The occurrences that each singer spent in each position (P1-P5) did depend on rehearsals (for singer 1: $\chi^2(16) = 55.1, p < 0.001$; for singer 2: $\chi^2(16) = 70.2, p < 0.001$; for singer 3: $\chi^2(16) = 63.6, p < 0.001$; for singer 4: $\chi^2(16) = 42.8, p < 0.001$; for singer 5: $\chi^2(16) = 54.0, p < 0.001$). This demonstrates that the tendency to precede/lag co-performers was significantly associated with the rehearsal sessions (i.e. R1-R5). Figure 6 illustrates the time spent in each position for each singer across the rehearsals. Interestingly, the bass (S5) spent most time in position 1 in rehearsals 1-4, therefore mostly preceding all co-performers.

< Figure 6 about here >

An analysis of leadership as indexed by entering in position 1 followed. This showed that the distribution between singers varied significantly across rehearsal ($\chi^2(16) = 96.7, p < 0.001$). This result demonstrates that tendency to precede all co-performers did relate to the different rehearsals (i.e., R1-R5). Results from the goodness of fit chi-square test indicate that the observed frequencies of position 1 for each singer (see Figure 7) were not equally distributed across rehearsal 1($\chi^2(4) = 69.0, p < 0.001$), rehearsal 2($\chi^2(4) = 17.4, p = 0.002$), rehearsal 3 ($\chi^2(4) = 53.1, p < 0.001$), and rehearsal 4 ($\chi^2(4) = 27.6, p < 0.001$). Notably, there was no significant difference between singers in occupying the first position in rehearsal 5 ($\chi^2(4) = 6.4, p = 0.172$). This indicates that the tendency to precede all other co-performers

changed during the course of study: it was not equally distributed among the five singers in the first four rehearsals, but it was during the last rehearsal, as shown in Figure 7.

In summary, these results show that when calculated at the level of relationships between the pairs of singers, the five rehearsals did not affect the relationships. However, the tendency to precede/lag each co-performer was significantly associated with rehearsal number. Notably, the tendency to precede all co-performers became equally shared among the singers by the end of the first term of study.

< Figure 7 about here >

4 Discussion

This study analysed the evolution of sensorimotor synchronization between advanced singers in a newly-formed singing quintet ensemble, during five rehearsals spread across their first term of study. The developmental aspects of synchronization were analysed during and across rehearsals, and in relation to the pieces practised. Three measures of interpersonal synchronization were investigated: precision and consistency of synchronization, as quantified by the absolute and SD of absolute asynchronies, and tendency to precede or lag a co-performer, as indicated by the signed asynchronies. These measures were objectively quantified through the analysis of the acoustics and electrolaringograph recordings. Verbal discussions between the singers during the five rehearsals were also scrutinized in relation to reference to synchronization.

Precision significantly improved from the first to the last rehearsal. In each rehearsal, precision was better in piece A, the more homophonic piece, than piece B (more polyphonic). Notably, precision in piece A improved significantly only between the first two rehearsals, but improved across the whole term of study in piece B. This suggests that the complexity of the piece being practised might affect the precision of synchronization between performers in ensembles. Singers practising a homophonic piece might significantly improve the precision of interpersonal coordination with only two rehearsals, establishing a stable degree of synchronization for the remaining rehearsals. Conversely, with a more complex piece, performers might need several rehearsals to establish a stable degree of synchronization. Further studies that increase the number of rehearsals analysed will inform whether/when singers establish a higher degree of synchronization in piece B, the more complex material.

Synchronization in piece A was more consistent than piece B in each rehearsal, as quantified by the SD of absolute asynchronies. The consistency of sensorimotor synchronization did not change in piece A during the full term of study. The consistency improved significantly between the first two rehearsals of piece B and then remained stable during the remaining rehearsals. These findings suggest that the piece being rehearsed might interact with rehearsal to affect the consistency of synchronization.

Analyses show that while singers varied in the balance of leadership (as indexed by preceding all other voices), across the first four rehearsals, by the final rehearsal no significant differences between the members of the quintet were apparent in occupying the first position. Although the analysis of the rank order positions does not offer a thorough analysis of the leader-follower relationships, these results suggest that the tendency to precede all co-performers changes across rehearsals, becoming equally distributed among singers toward the end of a first-term of study. These results further expand findings based on single laboratory sessions, suggesting a complex pattern of relationships between string players in ensemble quartets, rather than a clearer separation of roles[18,19]. The previous investigations provided a

single snapshot of the leader-follower relationships in music ensemble, reporting: i) a unidirectional dependence of Viola on Violin I, and of Violin I on Cello; and, ii) a bidirectional dependence between Violin II and Cello, and Violin II and Viola. This study sheds some light on the developmental aspects of the group relationships in music ensembles, finding an equally distributed tendency to precede all other co-performers by the end of the first term of study.

In addition, the above findings regarding the relationship between rehearsal number and synchronization did not vary largely among pairs of singers and time categories. Notably, synchronisation results were also consistent between pre- and post-rehearsal, suggesting that the individual rehearsal might not affect the synchronization. Singers were not told to focus on synchronization, but on expressiveness; they may improve precision and consistency of synchronization in different rehearsals if temporal coordination is the goal of the rehearsal.

Interestingly, the improvements in the synchronization observed across rehearsals are not linked to any specific targeted practice of the singers to improve synchronization, as demonstrated by the lack of specific reference to synchronization in the verbal discussions during the five rehearsals. Differences in the synchronization observed in the study across a first term of study might be related to a number of different extraneous variables. External factors occurring between rehearsals might have elicited an improvement in the synchronization. Singers were rehearsing the MA pieces between the five lab rehearsal sessions, and the more time spent together as an established ensemble during the course of the study might have elicited an improvement in the synchronization. Further studies should analyse the role of rehearsal in more depth to understand whether the rehearsal has a significant effect on the synchronization between musicians in ensemble.

5 Limitations and future work

Precision of synchronization improved between the first two rehearsals in piece A, and improved consistently in piece B across the term of study. It is now of interest to investigate whether this improvement is perceivable. A listening test including multiple recordings of the same pieces for each rehearsal is planned, analysing whether the performers, other musicians and non-experts might perceive a change in the degree of synchronization.

Further research should also investigate the repeatability of the above findings across different quintets, analysing whether these results typify the ensemble. Future investigations should also consider the effects of musicians' expertise, investigating whether the skill development influences the evolution of sensorimotor synchronization in singing quintet ensembles.

6 Conclusion

This study analysed the evolution of synchronisation between advanced singing students during their first term of study, in relation to the musical content of the piece being rehearsed and leader-follower relationships, conceptualized as tendency to precede/lag the co-performers. Precision of synchronization increased across rehearsals depending on the piece being rehearsed: it improved between the first two rehearsals in the less complex piece, piece A, and consistently across the five rehearsals in the most complex piece, piece B. Likewise, consistency of synchronization was piece-specific: it did not change during the first term of study in piece A, but improved in the first two rehearsals in piece B. Finally, the tendency for members of the ensemble to precede/lag the others differed significantly across rehearsals, suggesting that leader-follower relationships changed in different rehearsals. The tendency to

precede all co-performers became equally shared among the 5 singers by the last rehearsal session.

The results reported here could have important implications for the tailoring of rehearsal strategies that could improve interpersonal synchronization in an ensemble setting. The study contributes to the investigation of interpersonal coordination between musicians, highlighting the developmental aspects of interpersonal synchronization in singing ensembles. The results of this study are of interest to psychology research, aimed at clarifying the psychological processes that characterize interpersonal coordination, non-verbal communication, and social interaction.

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Table

Table 1 Primary and nested fixed effect coefficients and significance. The β-fixed effect coefficients of rehearsal and piece on the predictor being considered (i.e., precision, consistency, and tendency to precede/lag) are given with reference to the specific base level of the factor, i.e. rehearsal 2, 3, 4 and 5 *versus* the base level rehearsal 1, and piece B *versus* piece A. The β-fixed effect coefficients indicate that for each 1 unit increase in the predictor being considered, the effect of the given predictor changes by the amount specified by the β coefficient. For example, for each 1 unit increase in the precision of rehearsal 1, precision computed in rehearsal 2 decreases by 9.7 units. n.s.= not statistical significant; ***=*p<0.001*.

Parameter	**Fixed effects**	**Fixed effect coefficients and significance**				
		Rehearsal 1	*Rehearsal 2*	*Rehearsal 3*	*Rehearsal 4*	*Rehearsal 5*
Precision						
	Rehearsals		β=-9.7***, t(40505)=-5.4	β=-6.8***, t(40505)=-3.8	β=-8.8***, t(40505)=-4.9	β=-11.9***, t(40505)=-6.6
	Pieces	β=49.1***, t(40532)=23.5	β=32.4***, t(40532)=15. 5	β=30.7***, t(40532)=14.7	β=23.4***, t(40533)=11.2	β=17.7***, t(40532)=8.5
Consistency						
	Rehearsals		n.s.	n.s.	n.s.	n.s.
	Pieces	β=48.9***, t(3794)=14.1	β=19.5***, t(3798)=6.0	β=14.2***, t(3798)=4.4	β=13.4***, t(3799)=4.1	β=10.5***, t(3799)=3.2
Tendency						
	Rehearsals		n.s.	n.s.	n.s.	n.s.
	Pieces	β=10.2***, t(39783)=4.0	n.s.	n.s.	n.s.	n.s.

646 Figures captions

647 Figure 1. Piece A used for the study. The full set of notes was used for the analysis of
648 synchronization between singers.

649 Figure 2. Piece B used for the study, showing the notes, highlighted with *, and the time
650 categories upon which the analysis is based.

651 Figure 3. Excerpt from the 5 Lx signals showing the temporal rank order regarding the
652 entrances of the 5 singers performing the onset of the first note of piece A recorded during
653 rehearsal 5. Based on the temporal entrance order from position 1 (P1) to position 5 (P5), the
654 resulting temporal sequence observed here was S3-S4-S1-S5-S2, where S3 and S2 were the
655 first and last singer to precede and lag all-co-performers, respectively.

656 Figure 4. Precision of synchronization: A) by rehearsal, and B) by interaction between
657 rehearsal and piece. Error bars represent 95% CI of the mean. p-values have been adjusted
658 using the Holm method. $***= p < 0.001$

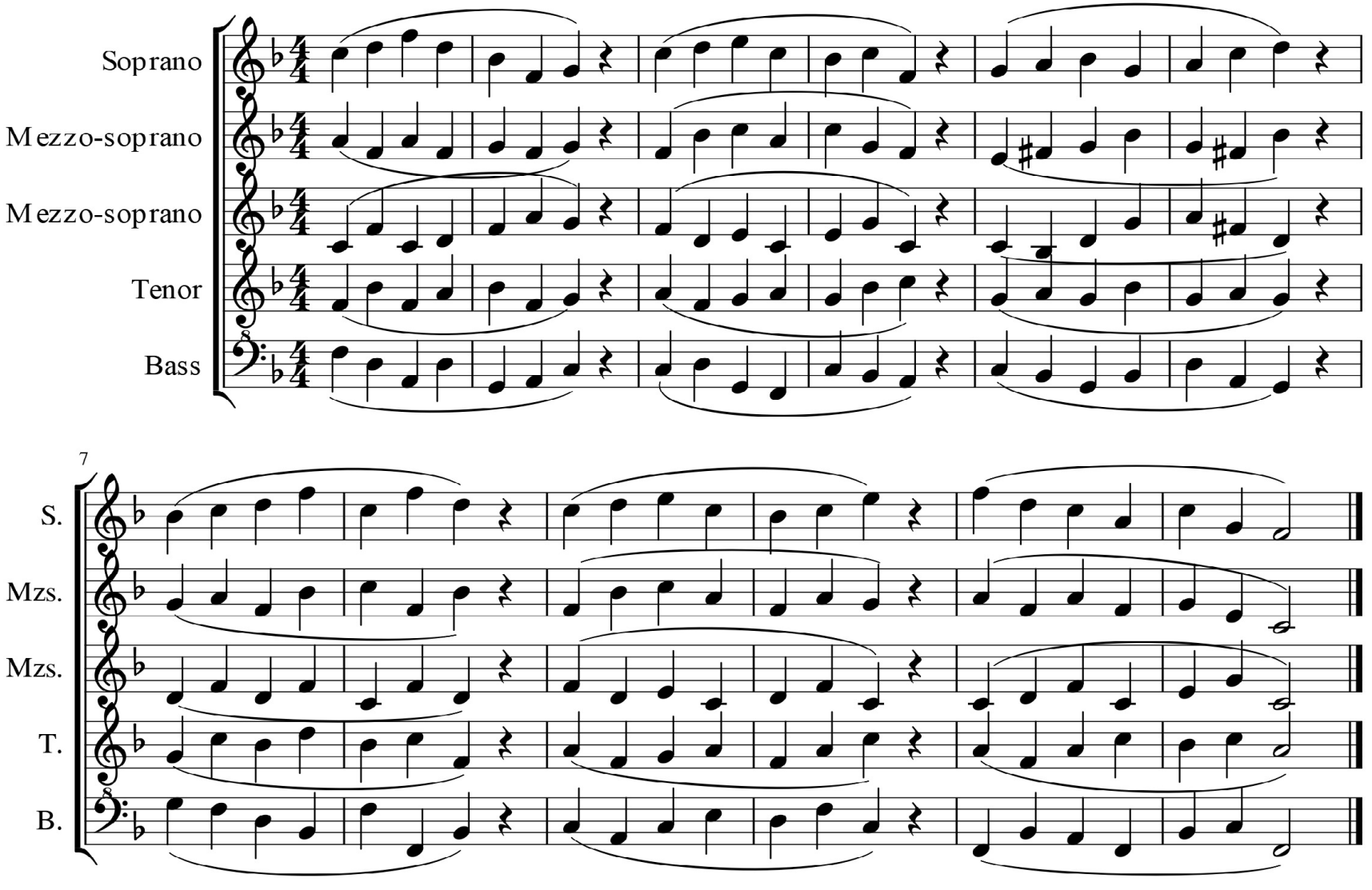
659 Figure 5. Consistency of synchronization: A) by rehearsal, and B) by interaction between
660 rehearsal and piece. Error bars represent 95% CI of the mean. p-values have been adjusted
661 using the Holm method. $**= p < 0.01;\ ***= p < 0.001.$

662 Figure 6. Occurrences of entry positions from position 1 to position 5 across rehearsals
663 computed for each singer

664 Figure 7. Distribution of position 1 across rehearsals, based on the number of occurrences
665 each singer preceded all co-performers

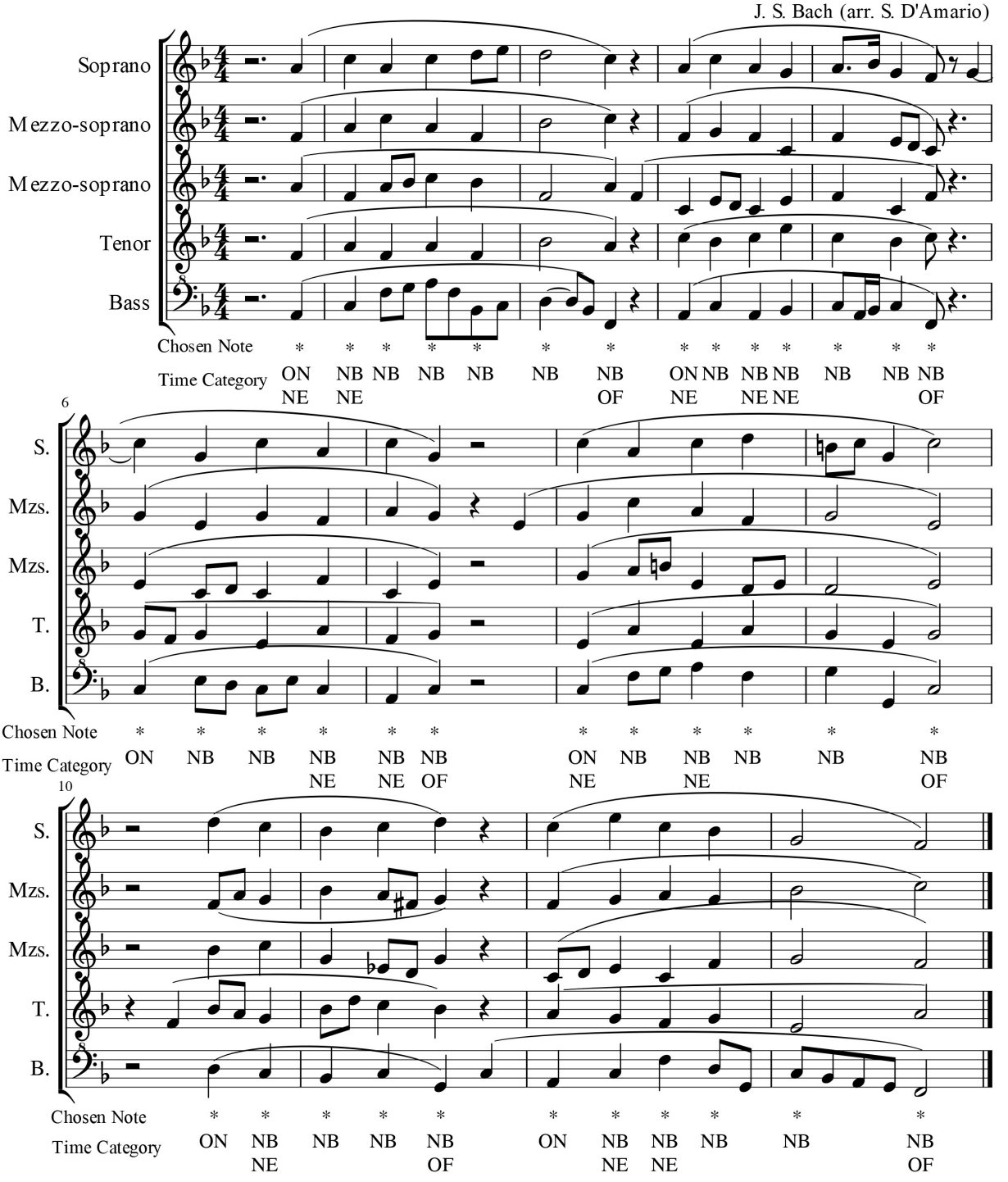
Piece A

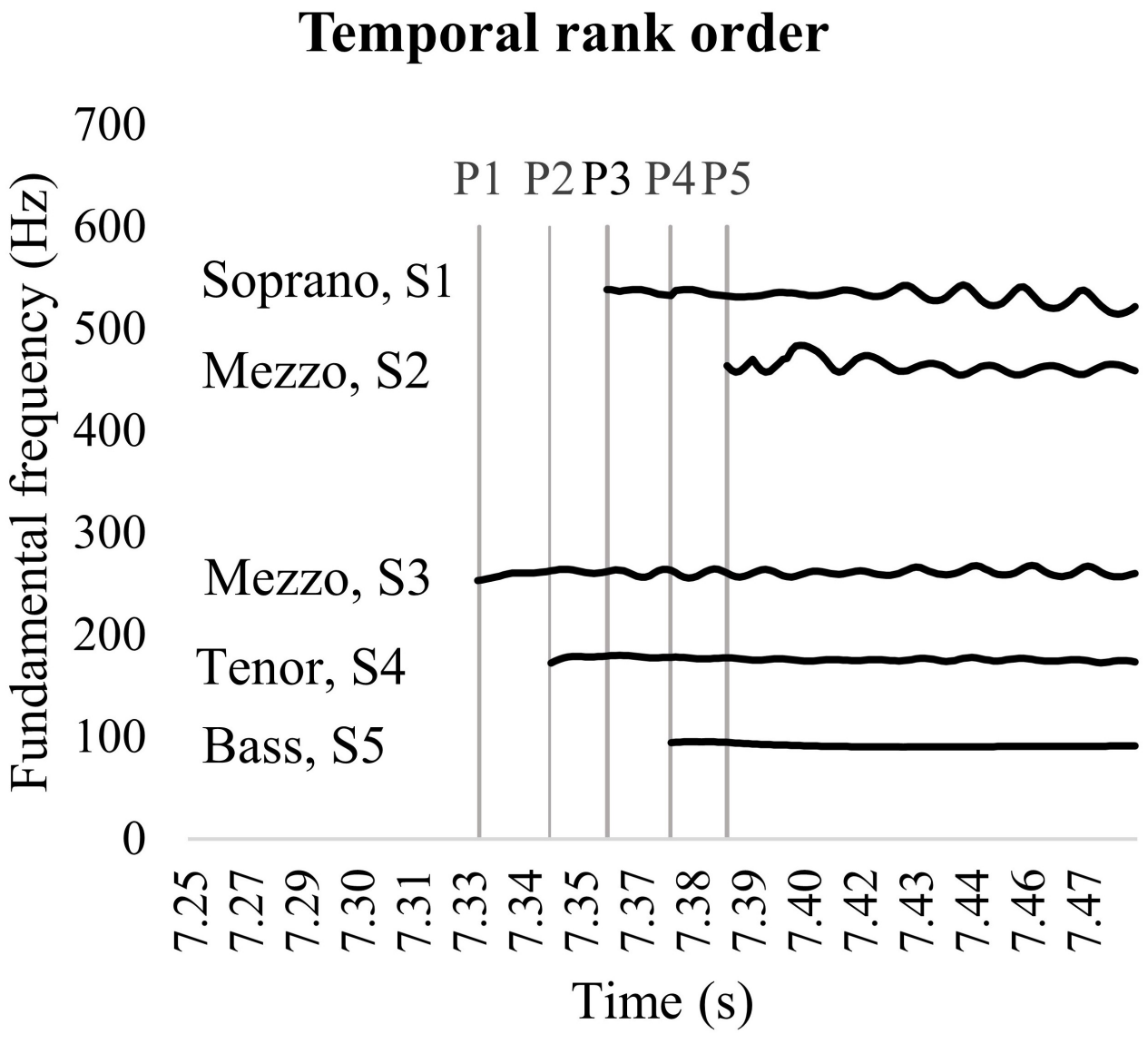
J. S. Bach (arr. S. D'Amario)

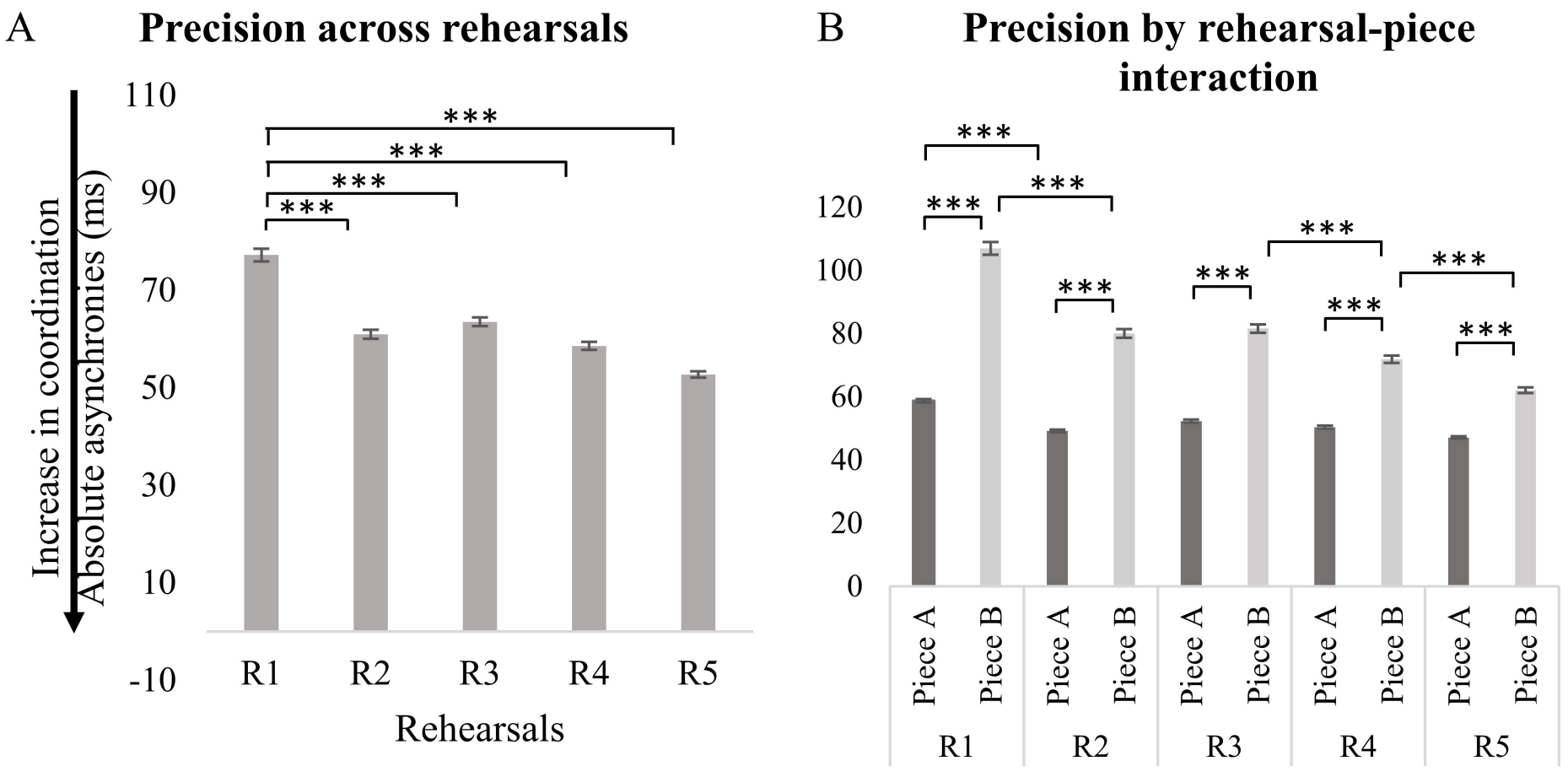


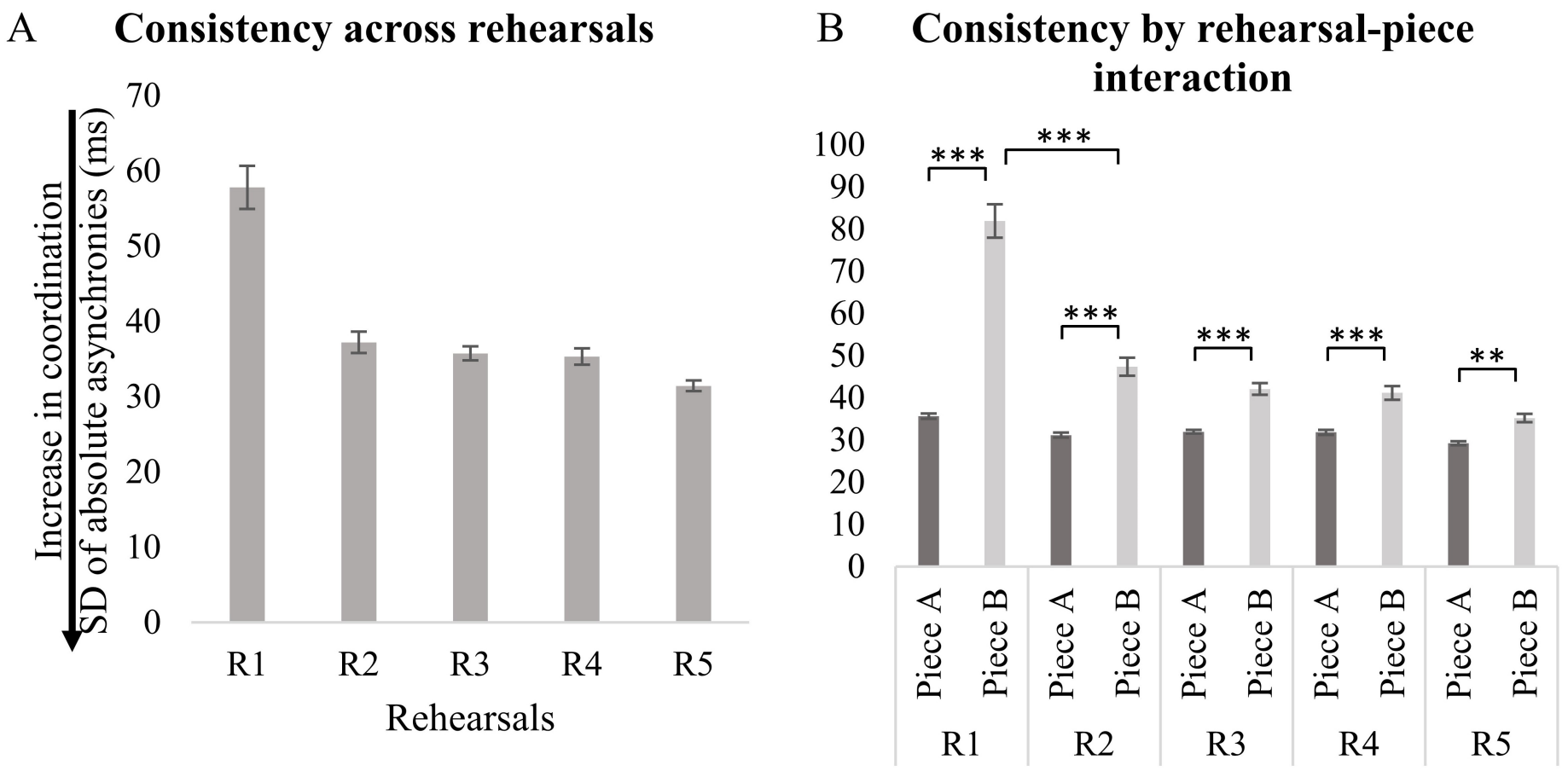
Piece B

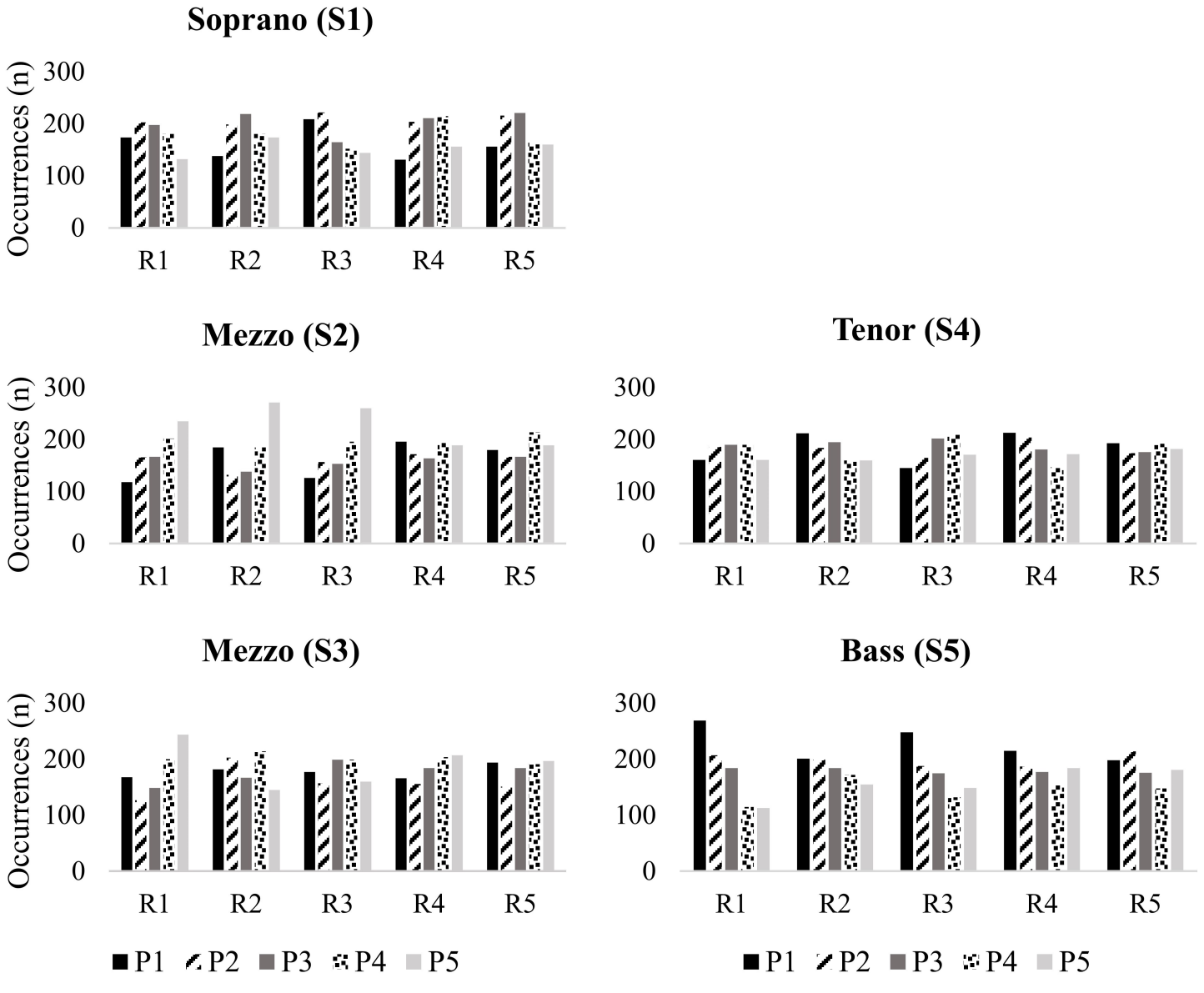
J. S. Bach (arr. S. D'Amario)

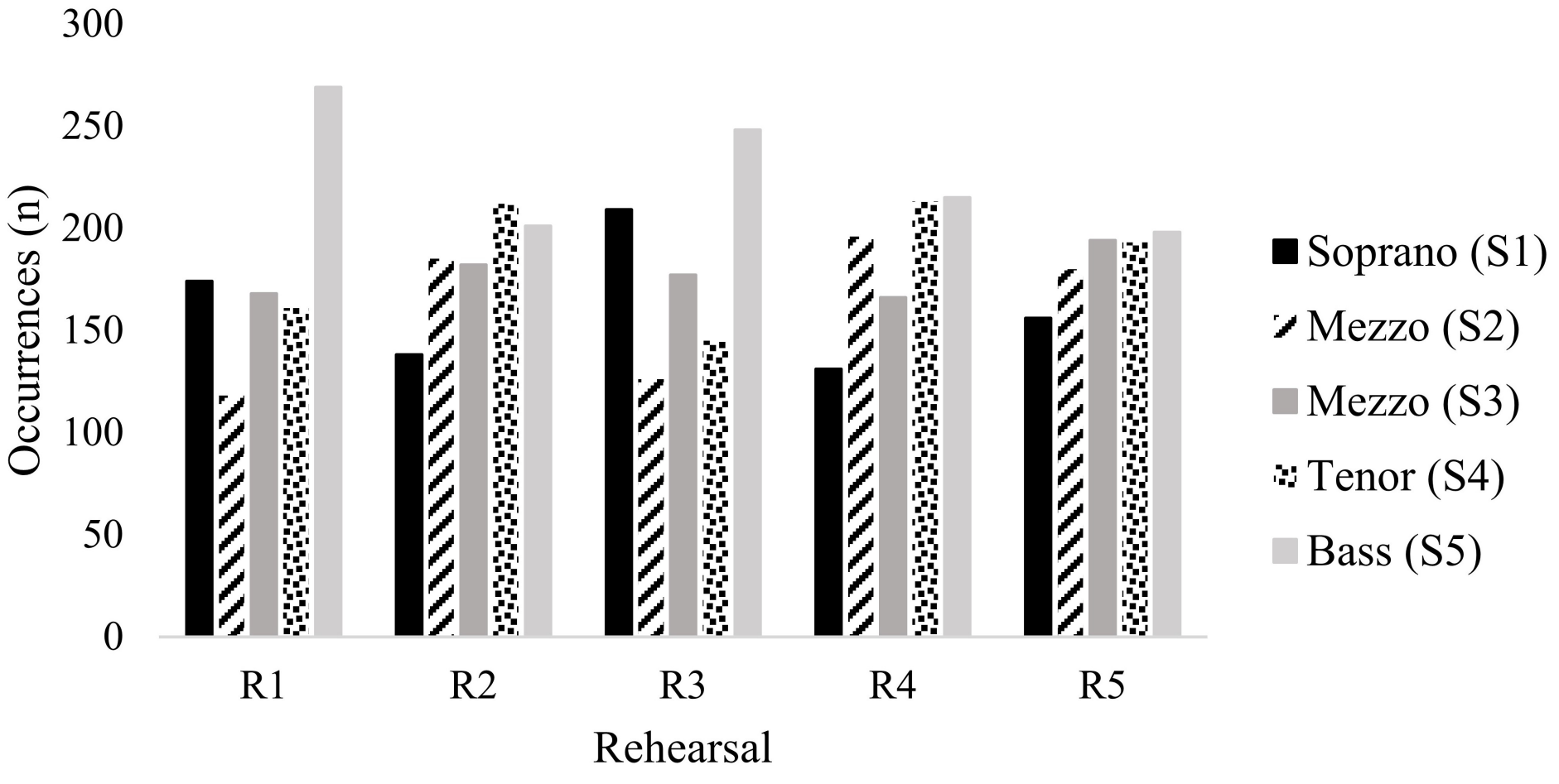



Temporal rank order
Fundamental frequency (Hz)
700
600
500
400
300
200
100
0
P1
P2
P3
P4
P5
Soprano, S1
Mezzo, S2
Mezzo, S3
Tenor, S4
Bass, S5
7.25
7.27
7.29
7.30
7.31
7.33
7.34
7.35
7.37
7.38
7.39
7.40
7.42
7.43
7.44
7.46
7.47
Time (s)


A
Precision across rehearsals
Increase in coordination
Absolute asynchronies (ms)
110
90
70
50
30
10
-10
***
***
***
***
R1
R2
R3
R4
R5
Rehearsals
B
Precision by rehearsal-piece interaction
120
100
80
60
40
20
0
***
***
***
***
***
***
***
***
***
***
Piece A
Piece B
R1
R2
R3
R4
R5


A
Consistency across rehearsals
Increase in coordination
SD of absolute asynchronies (ms)
70
60
50
40
30
20
10
0
R1
R2
R3
R4
R5
Rehearsals
B
Consistency by rehearsal-piece interaction
100
90
80
70
60
50
40
30
20
10
0
***
***
***
***
***
***
**
Piece A
Piece B
R1
R2
R3
R4
R5


Soprano (S1)
Occurrences (n)
300
200
100
0
R1
R2
R3
R4
R5
Mezzo (S2)
Occurrences (n)
300
200
100
0
R1
R2
R3
R4
R5
Tenor (S4)
300
200
100
0
R1
R2
R3
R4
R5
Mezzo (S3)
Occurrences (n)
300
200
100
0
R1
R2
R3
R4
R5
Bass (S5)
300
200
100
0
R1
R2
R3
R4
R5
P1
P2
P3
P4
P5
P1
P2
P3
P4
P5


Position 1 distribution for each singer and rehearsal
300
250
200
150
100
50
0
Occurrences (n)
R1
R2
R3
R4
R5
Rehearsal
Soprano (S1)
Mezzo (S2)
Mezzo (S3)
Tenor (S4)
Bass (S5)