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Not just in sync: Relations between partners' actions influence the sense of joint agency during joint action

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Abstract

When people perform joint actions together, they often experience a sense of joint agency ("we did that together"). The current study investigated whether the relations between partners' actions within joint actions that require precise interpersonal synchrony influence joint agency, above and beyond the degree of synchrony partners achieve. We employed a mixed-methods approach that combined a quantitative experiment with a qualitative analysis of post-experiment interviews. Partners produced synchronized tone sequences that comprised either constant pitch sequences (simple temporal alignment between partners' actions) or musical duets (complex metrical and harmonic relations between partners' actions). Participants reported stronger joint agency for duets than constant pitches, when comparing trials with equally good synchronization. Post-experiment interviews revealed that joint agency was also influenced by participants' knowledge of the music and their perceptions of task performance, difficulty, and enjoyability. These findings further our understanding of joint agency for joint actions that require precise interpersonal synchrony.

Keywords: sense of agency, joint agency, joint action, interpersonal synchrony, mixed methods

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1. Introduction

As people go about their everyday lives, they usually experience a sense of *agency* over their actions, i.e., a feeling of generating and controlling actions and their corresponding consequences (Haggard & Tsakiris, 2009). The sense of agency has been investigated in solo action (e.g., Haggard & Eitam, 2015; Wen & Imamizu, 2022) and in social contexts ranging from the mere presence of others to joint actions in which people coordinate their actions with each other to achieve a shared goal (Sebanz et al., 2006; see Loehr, 2022; Silver et al., 2020; Villa et al., 2022; Zapparoli et al., 2022 for recent reviews). Joint actions pose unique challenges for understanding the sense of agency (Loehr, 2022; Pacherie, 2012). Specifically, because joint actions are comprised of individual actions (e.g., producing a series of tones) that must be coordinated to achieve a collective goal (e.g., performing a musical duet), people engaged in joint action can have a sense of agency not only at the individual level ("I produced my tones"), but also at the collective level ("We performed the duet together"). The latter is referred to as *joint agency.* The sense of joint agency can take multiple forms, including a sense that agency is distributed among co-actors (shared agency; Pacherie, 2012; Seemann, 2009; Tollefsen, 2014) or a sense that co-performers are "acting as one" or as a single unit (united or we-agency; Loehr, 2022; McNeil, 1995; Pacherie, 2012). The purpose of the current study was to investigate how relations between partners' individual actions influence their sense of joint agency during joint actions that require precise interpersonal synchrony.

Three recent developments in the joint action and joint agency literatures motivated the current study. The first development concerns our understanding of the mental representations that underlie joint action. Well-established findings show that people engaged in joint action form representations of each other's individual actions (see Knoblich et al., 2011, for a review). More recent work demonstrates that people also represent the collective goal of the joint action (e.g., Della Gatta et al., 2017; Loehr et al., 2013; Loehr & Vesper, 2016). Most importantly for the current study, researchers have just begun to establish that mental representations of joint action also include the *relations* between partners' actions (Sebanz & Knoblich, 2021). For example, advance knowledge about the configural relations between partners' actions (i.e., knowing whether a partner will perform the *same* or a *different* hand configuration as oneself) facilitates performance and modulates brain activity related to action planning, even when the actions themselves are not pre-specified (Kourtis et al., 2019). Other relations between partners' actions that have recently been investigated include temporal relations (e.g., whether partners must act in synchrony versus take turns; Milward & Sebanz, 2018) and harmonic relations (e.g., which harmonies are produced when tones produced by two performers are combined to create a musical duet; Aucouturier & Canonne, 2017).

The second development relevant to the current study is emerging evidence that the relations between partners' actions have a relatively stronger impact on the sense of joint agency than does information about one's own individual actions. This evidence comes from a set of studies in which two partners coordinated their keypresses to move a single dot from the centre of a screen to one of several targets, and rated both their sense of joint agency and their sense of individual self-agency after each trial (Le Bars et al., 2020a, 2020b). Le Bars et al. (2020a) demonstrated that joint agency is stronger when people share the *same* movement intentions (both partners intend to move to the same target) compared to when they might hold *different* movement intentions (each partner could intend to move to a different target). Le Bars et al.

(2020b) demonstrated that people report stronger joint agency when they and their partner make *equal* contributions to a joint action (i.e., when both partners have to travel the same distance to reach a target) compared to when they made *unequal* contributions (one partner has to travel farther than the other). In these studies, the relatively strong influence of relations between partners' actions on joint agency stands in contrast to a relatively weak influence of each person's individual actions. For example, the distance an individual had to travel to the target, as well as the degree of motor noise added to their keypresses, had small impacts on joint agency and instead more strongly influenced people's sense of individual self-agency.

The third development relevant to the current study is preliminary evidence concerning the primacy of coordination performance as a cue to joint agency in joint actions that require partners to synchronize their actions with each other. Specifically, two recent studies showed that coordination performance was the only cue that influenced joint agency when partners' main goal was to synchronize their actions with each other; other cues manipulated in each study did not impact joint agency. First, Reddish et al. (2020) had partners synchronize forearm movements together and found that people reported stronger joint agency when they perceived a greater degree of synchrony between themselves and their partner. However, neither the participant's role in the joint action (leader versus follower) nor the instructions they received (explicitly versus implicitly requiring synchrony) influenced joint agency. Second, Christensen et al. (2022) had partners play simple musical duets together and found that people reported stronger joint agency when they were better synchronized with their partner. However, neither the duet part performed by the participant (melody versus accompaniment) nor the pitch distance between the two parts (closer together or father apart in pitch space) influenced joint agency. Findings from these two studies complement those of earlier studies showing that coordination performance is also a strong predictor of joint agency in joint actions that require temporally coordinated turn-taking (e.g., Bolt et al, 2016; Dell'Anna et al., 2020). However, the more recent findings go a step further by suggesting the possibility that synchrony might be the *only* cue that drives people's sense of joint agency in joint actions that require interpersonal synchrony. Note, though, that such a possibility would stand in contrast with evidence that multiple cues influence joint agency in joint actions that do not require interpersonal synchrony (Loehr, 2022).

Considering these three developments together, one goal of the current study was to investigate whether the relations between partners' actions influence joint agency in a task that requires interpersonal synchrony, above and beyond the degree of synchrony partners achieve within the task. A variety of joint actions require precise interpersonal synchrony and elicit a sense of joint agency, including marching, dancing, team sports such as rowing, and group music performance (Loehr, 2022). For the current study, we elected to use an experimental analog of duet music performance, because it requires precise interpersonal synchrony between partners, provides an ecologically valid task that also allows for careful experimental control (D'Ausilio et al., 2015; Acquadro et al, 2016), and can be performed even by novices if provided with simple musical stimuli or musical devices (e.g., Loehr & Vesper, 2016; Novembre et al., 2015). Here, we asked pairs of participants to produce sequences of synchronized tones together using electronic music boxes. Electronic music boxes transform simple rotational movements into digital auditory output, as shown in Figure 1A, and were designed to allow people with no musical experience to perform musical duets together (Novembre et al., 2015). We experimentally manipulated the relations between partners' actions by asking partners to synchronize either a) a simple melody produced by one partner with an accompaniment produced by the other partner, creating a musical duet (Figure 1B), or b) two sequences of tones

whose pitches remained constant throughout the sequence (e.g., one partner produced the tones CCCC… and the other produced the tones FFFF…, where letters indicate the pitch of each tone; Figure 1C). As illustrated in Figure 1, both types of sequences required participants to synchronize pairs of tone onsets (e.g., C with F), and thus both types of sequences required *temporal alignment* between partners' actions. However, musical duets entailed additional *metrical and harmonic relations* between partners' actions, as we explain next.

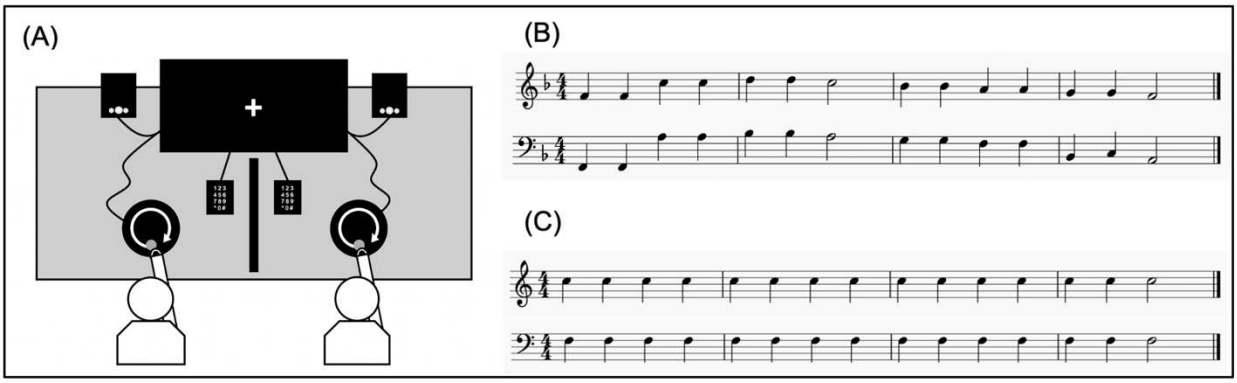

*Figure 1***.** (A) Schematic diagram of the experimental set-up. Circles represent electronic music boxes and arrows indicate direction of rotation. (B) Example musical duet (top staff: melody; bottom staff: accompaniment). (C) Example constant pitch sequence (top staff: higher-pitch part; bottom staff: lower-pitch part).

First, *harmonic relations* refers to the alignment of the melody with the accompaniment that creates the harmonic structure of a musical duet. In other words, the first note of the melody aligns with the first note of the accompaniment, the second note of the melody aligns with the second note of the accompaniment, and so on. When the notes are appropriately aligned, people perceive harmonic relations between the melody and accompaniment that are comprised of hierarchically organized tones, chords, and keys, and that unfold dynamically as the musical piece progresses (Krumhansl, 2000). In contrast, when two people coordinate two sequences of constant pitches, there are limited harmonic relations between the higher- and lower-pitch parts because the harmony remains unchanged throughout the sequence. Second, *metrical relations* refers to the metrical structure (i.e., a series of hierarchically organized strong and weak beats) that people perceive when they listen to or produce musical duets (Lerdahl & Jackendoff, 1983; Palmer & Jungers, 2003; Palmer & Krumhansl, 1990). Metrical structure develops from regularly occurring accents in the music, which can arise from changes in melodic contour (i.e., the direction of pitch change from note to note; Temperley & Bartlette, 2002) or changes in harmony (White, 2018), as well as from changes in timbre or loudness (Cusack & Roberts, 2000; Tekman, 2002; but note that participants could not manipulate tone timbre or loudness using the electronic music boxes). In contrast, when people coordinate two sequences of constant pitches, the perceived metrical structure is limited because there are no changes in melodic contour or harmony (or timbre or loudness) throughout the sequence. In sum, then, by manipulating whether partners synchronized musical duets versus constant pitch sequences, we created joint actions with simple *temporal alignment relations* between partners' actions versus more complex *metrical and harmonic relations* between their actions, respectively.

A second goal of the current study was to probe the breadth of cues that influenced people's sense of joint agency in our experimental tasks. Previous research on the sense of

agency in solo action has shown that people derive their sense of individual self-agency by integrating cues from multiple sources (Moore & Fletcher, 2012; Synofzik et al., 2013). Likewise, multiple cues influence people's sense of joint agency in joint actions that do not require interpersonal synchrony (Loehr, 2022; Zapparoli et al., 2022). We anticipated that the same might be true for joint actions that do require interpersonal synchrony, and we employed a mixed-methods research design to explore this possibility. Specifically, we combined our experimental manipulation and accompanying analysis of joint agency ratings made after each experimental trial with interviews of both partners after the experimental trials were complete. In the interviews, we probed participants' perceptions of the cues that influenced their sense of joint agency when performing each type of sequence. We employed this mixed-methods approach to capitalize on the complementary methodological strengths of the quantitative and qualitative components of our design (Johnson & Onwuegbuzie, 2004). Specifically, our experimental manipulation and accompanying quantitative analysis allowed us to test our *a priori* hypotheses and to directly assess the effect of relations between partners' actions on joint agency, while our qualitative analysis of post-experiment interviews allowed us to inductively compile information about the broader set of cues that influenced people's sense of joint agency. A key strength of mixed-methods research is that it can address both confirmatory and exploratory research questions simultaneously (Teddlie & Tashakkori, 2003; Venkatesh et al., 2013). Moreover, a given mixed-methods study can serve multiple purposes (Greene et al., 1989; Tashakkori & Teddlie, 2008; Venkatesh et al., 2013), among which our goals included *corroboration* (that is, we sought converging evidence that people use the relations between partners' actions as a cue to joint agency from both the quantitative and qualitative data), *complementarity* (we sought to gain complementary views of the cues that influence joint agency from both sets of data), and *completeness* (we sought to obtain a more complete understanding of the cues that influence joint agency in tasks that require interpersonal synchrony). Our mixed-methods approach fits with other research that has successfully used mixed-methods to shed light on cognitive processes (see Ormerod & Ball, 2017), in domains such as reasoning and problem-solving (Heyvaert et al., 2018; McCrudden & Barnes, 2015), improvisation (Ilari et al., 2017), and achieving flow states (Clementson, 2019; Horwitz et al., 2021).

1.1 The Current Study

In sum, the current study had two goals. First, we sought to investigate whether the relations between partners' actions influence people's sense of joint agency in joint actions that require precise interpersonal synchrony, above and beyond the degree of synchrony partners achieve. Second, we sought to probe the broader set of cues that might influence joint agency during such joint actions. We employed a mixed-methods design that combined a *quantitative experimental design and analysis* of participants' joint agency ratings with a *qualitative thematic analysis* of participants' post-experiment interview responses. The quantitative experimental design entailed a within-subjects manipulation of the relations between partners' actions, which was implemented by having partners synchronize either a) constant pitch sequences that entailed a simple temporal alignment relation between partners' actions or b) musical duets that entailed additional metrical and harmonic relations between partners' actions. Because both sequence types included the same simple temporal alignment relation of tone onset synchronization (see Figure 1), we expected that partners would achieve similar levels of synchrony for both sequence types.

Our primary *a priori* hypothesis was that people would report stronger joint agency for musical duets compared to constant pitch sequences, even when they achieved equivalent synchrony for both sequence types. This hypothesis was based on research showing that people's mental representations of joint action include the relations between partners' actions (Sebanz & Knoblich, 2021), and that relations between partners' actions influence joint agency in tasks that do not require interpersonal synchrony (Le Bars et al., 2020a, 2020b). An alternative possibility was that the degree of synchrony partners achieved would be the primary cue driving joint agency, in line with findings from Reddish et al. (2020) and Christensen et al. (2022). In that case, no difference in joint agency would be expected between the musical duets and constant pitches if partners achieved equivalent synchrony in both cases. With respect to our qualitative analysis of participants' interview responses, one possibility was that participants would primarily focus on the degree of synchrony they achieved with each type of sequence. Another possibility, which we considered more likely, was that participants would mention synchrony as one cue among many. The latter outcome would provide converging evidence that synchrony is not the only cue people rely on when deriving their sense of joint agency, even in a task that requires precise interpersonal synchrony.

2. Method

2.1 Participants

Fifty-eight undergraduate students (44 women, mean age = 21.64, *SD* = 4.67) participated in the study. Participants were recruited in pairs regardless of gender composition. Sixteen pairs were comprised of two women, 12 pairs were mixed-gender, and one pair was comprised of two men. We aimed to collect data from a total of 32 pairs to achieve a multiple of complete counterbalancing and to align with sample sizes from our previous investigations of joint agency. However, data collection was stopped after 29 pairs due to the Covid-19 pandemic. Ethics approval was obtained from the institutional review board before participant recruitment, and participants gave informed consent at the beginning of the study. Participants were compensated with course credit for an undergraduate psychology course.

2.2 Design

The study used a concurrent mixed-methods design (Fetters et al., 2013), in which quantitative and qualitative data were collected in parallel. Quantitative data were collected via a within-subjects experimental manipulation in which partners produced two types of synchronized sequences and rated their sense of joint agency after each sequence. The two sequence types were *musical duets,* which were comprised of familiar melodies with supporting accompaniments, and *constant pitch sequences,* which were comprised of constant pitches spaced a twelfth apart. Qualitative data were collected immediately after the experimental trials by asking each partner separately to complete a short post-experiment interview about their ratings of joint agency for each sequence type. Quantitative and qualitative were first analyzed separately, as presented in the Results section, and then compared and contrasted, as presented in the Discussion section. Thus, data integration occurred at the methods level by *connecting* the data through the sampling frame, and data integration occurred at the interpretation level through a *weaving narrative* approach, in which the quantitative and qualitative findings were considered together on a concept-by-concept basis (see Fetters et al., 2013).

2.3 Apparatus and stimulus material

Participants produced tone sequences using modified versions of the electronic music box described by Novembre et al. (2015), which are depicted schematically in Figure 1A. An electronic music box consists of a rotating disk with an attached handle. As the disk is rotated, a computer produces pitches at specific degrees of rotation. In our case, the electronic music boxes were programmed to produce either a quarter note (i.e., a tone with a duration of one beat) for each 90º rotation, or a half note (i.e., a tone with a duration of two beats) for a 180º rotation. Thus, if participants rotated the disk at a rate of one complete circle every 2s, they produced one beat (usually marked by a quarter note) every 500 ms.

During the experiment, participants were instructed to rotate their disks in synchrony with each other to produce either a musical duet or a constant pitch sequence. We composed five musical duets for the study (see Figure 1B for an example). For the melodies, we chose five familiar children's songs that were recognizable when composed almost entirely of quarter notes (Mary Had a Little Lamb, which was used for the practice phase of the experiment; Twinkle Twinkle Little Star, B.I.N.G.O, Hush Little Baby, and Yankee Doodle, which were used for the test phase of the experiment). We used the first two phrases of each song because these phrases establish and expand on the key of the song. Each musical duet was four bars (16 beats) long. Pitch onsets occurred at 14 of the 16 beat positions, because the melodies were composed entirely of quarter notes with the exception that each melody contained two half notes. For two of the test phase melodies, both half notes occurred at the end of the second phrase (at beat positions 13 and 15). For the other two test phase melodies, one half note occurred at the end of the first phrase and the other at the end of the second phrase (beat positions 7 and 15, as shown in Figure 1B). Accompaniments were composed such that pitch onsets always occurred in the same beat positions as in the associated melody and all notes were at least one octave below the melody.

For the constant pitch sequences, we chose four different pairs of tones to complement the four musical duets. An example constant pitch sequence is shown in Figure 1C. Each constant pitch sequence consisted of a higher-pitch part (note A4, C5, E♭5, or F♯5, respectively) and a lower-pitch part. The lower-pitch part was one twelfth (19 semitones) below the higher-pitch part to create a similar pitch separation between parts as in the musical duets. Constant pitch sequences were also 16 beats long and were comprised entirely of quarter notes with the exception of one half note that occurred at the end of the last bar (beat position 15).

During the experiment, participants sat next to each other in a soundproof booth. A computer screen was placed between them, approximately 60 cm from the table edge. Each participant had an electronic music box placed directly in front of them, approximately 30 cm from table edge, and a numeric keypad placed to the side, which they used to enter their joint agency ratings. An occluder was placed between the two participants to prevent them from seeing each other's hand movements and numerical ratings. Auditory stimuli were presented through speakers on both sides of the computer screen. Max 7 software (Cycling '74, 2014), running in the Windows 7 OS on a Dell Precision T3600 computer, controlled the experiment and presented visual and auditory stimuli. The Max program received the rotational position of each music box at a sampling rate of 333 Hz, and produced tones specified by a Musical Instrument Digital Interface (MIDI) file when the corresponding rotational position was reached. Each MIDI file specified the required pitches as well as pitch loudness (MIDI velocity of 76) and duration (the offset of each pitch was simultaneous with the onset of the next pitch in the sequence). Within Max, the fluidsynth~ function (fluidsynth.org) within R-udp player (Gjertsen,

2019) was used to play opensource Akai Steinway piano samples for the sequence pitches and percussion (clave) samples for the metronome that preceded sequence production.

2.4 Procedure

The experiment began by having participants practice starting on time following a 4-beat countdown. The countdown was presented using simultaneous visual and auditory cues (numerals and metronome sounds) at 500 ms intervals. Participants were instructed to move the music box's handle in synchrony with the fifth metronome sound. Movement of the handle immediately elicited a single tone. Participants received visual feedback indicating the asynchrony between their tone and the metronome, and they practiced until they could consistently achieve satisfactory coordination with the metronome. Participants completed this practice session individually to ensure that both members of the pair could perform the task.

Next, the participants completed four practice blocks which alternated between musical duets and constant pitch sequences. Before the first practice block, the experimenter placed the occluder between the participants. Within each block, each participant first completed at least one solo trial in which they produced their part of the musical duet or constant pitch sequence alone. On solo trials, the auditory metronome continued after the countdown until the end of the sequence to guide the pace of the participant's performance. At the end of each solo trial, the participant received feedback indicating the asynchronies between the metronome and each tone they played, and they were required to repeat the solo trial if the asynchronies were too large (specifically, asynchronies were required to be <50 ms on 8 of the sequence's beats in the first practice block, with the criterion increasing to 9, 10, and 11 beats in the second to fourth blocks, respectively). After the solo trials, the participants completed at least one joint trial in which they practiced playing together. On joint trials, the metronome stopped after the countdown to ensure that participants synchronized with each other rather than the metronome. At the end of each joint trial, the participants received feedback indicating the asynchronies between their respective tones and were again required to repeat the joint trials until they passed the criterion (now increased to <150 ms asynchronies between tones).

Next, participants completed eight test blocks that alternated between musical duets and constant pitch sequences, with a short break after the fourth block. Each test block started with one solo trial for each participant. Participants then performed five joint trials. No performance feedback was presented during the test blocks. Musical duets and constant pitch sequences were presented in the same counterbalancing order in the practice and test blocks, determined as follows. First, we determined the order of the four songs and the four constant pitch sequences using separate balanced Latin Square designs, resulting in four orders for each sequence type. We then crossed the two sets of four orders together, resulting in a total of 16 counterbalancing orders. We also counterbalanced which sequence type was presented first, and which participant (seated on the right or left) played the melody/higher-pitch part first, across pairs.

Each trial started with an information screen that specified the name of the sequence to be performed (either a song title or the words "Constant pitch"), the type of trial (solo or joint), and who was going to play (the participant on the right, left, or both). The information screen also specified the part to be performed for solo trials (e.g., "Melody" or "High pitch") or the number of trials to be completed for joint trials. When the participants were ready, the experimenter pressed the spacebar, and the 4-beat metronome countdown began 500 ms later. After each joint trial in the test blocks, each participant was asked to rate their sense of joint agency using a modified version of the Inclusion of Other in the Self scale (Aron et al., 1992; see Himberg et al.,

2018, for a similar adaptation of this scale). The modified scale, shown in Figure A1 in the Appendix, consisted of seven pairs of circles, ranging from two circles that did not overlap at all to two circles that overlapped almost entirely. Participants were asked to "indicate which diagram best describes how integrated you felt with your partner while playing the e-music boxes together." We chose to use a visual analog scale rather than a numerical scale with verbal labels (such as "independent", "shared", and "united;" see, e.g., Dell'Anna et al., 2020), because we did not want experimenter-provided labels to influence participants' word choices in their descriptions of joint agency in the post-experiment interviews. We chose to use the broad phrase "how integrated you felt with your partner" as the stem of our rating scale, rather than the more commonly-used and specific stem "feelings of control," so that participants' ratings were not limited to a single aspect of joint agency but could instead encompass its multiple aspects (e.g., as discussed in Loehr, 2022, and Saint-Germier et al., 2021, and which we discuss further in the Discussion section). The participants entered their ratings in random order, determined separately for each trial and signaled by which participant's side of the screen the rating scale appeared on first.

After completing the test blocks, each participant completed a short semi-structured interview with the experimenter while their partner completed a demographics questionnaire outside of the sound-proof booth. The interview began with an open-ended question, "Can you tell me what your experience was like doing this?". Then, the participants were shown histograms of their ratings for the musical duets and for the constant pitch sequences. The experimenter explained the histograms and then asked participants to explain the reasons for their ratings of each sequence type. The experimenter prompted the participants to expand on their responses when appropriate. Participants were also asked how good it felt to play in each condition on a scale from 1-10 (see Figure A2 in the Appendix for the full set of interview questions). After the interviews, the participants were debriefed.

2.5 Data analysis

2.5.1 Quantitative analyses of experimental trials

2.5.1.1 Interpersonal synchrony

Before analyzing participants' joint agency ratings, we a) calculated partners' synchronization performance on each trial, b) removed trials with large synchronization errors from the dataset, and c) checked whether partners' overall synchronization performance differed between the two sequence types. We calculated partners' synchronization performance as follows. First, we used the rotation data from each participant's electronic music box to extract the onset time of each quarter note beat. Note that for the two musical duets with half notes at beat 7, no note sounded at beat 8. We nevertheless extracted the onset time of beat 8 from the continuous rotation data so that we had the same number of onsets for all musical duets and constant pitch sequences. We next calculated the absolute asynchrony between the two participants' note onsets at each beat. Then, we converted each asynchrony to a proportion of the inter-onset interval (IOI) from the preceding note onset to the current note onset (averaged across the two participants). This allowed us to compare asynchronies regardless of differences in performance speed between pairs or changes in performance speed over time (e.g., participants sometimes sped up or slowed down within a trial). Finally, we calculated the mean and standard deviation of the asynchronies separately for each trial.

We removed trials with large synchronization errors from the dataset to minimize potential effects of attributions of blame that may occur when large timing errors are made (e.g., if one

partner fell noticeably behind the other). First, we removed trials in which one participant in the pair produced more than two beats after their partner's last beat, i.e., after their partner had already finished playing (47 trials out of 1160). Then, separately for each pair, we removed any trial whose mean or *SD* asynchrony was more than 3*SD* above or below the overall mean or *SD,* respectively (an additional 21 trials; in total, 5.86% of trials were removed due to these synchronization errors). Because the mean and *SD* asynchrony values were highly correlated (r = .82), we report analyses of synchronization performance based on the mean asynchrony only. After removing outliers, mean asynchrony values in the dataset ranged from 0-1.3 beats (of which 97.25% fell between 0-1 beats).

We compared partners' synchronization performance for the two sequence types using a linear mixed-effects model analysis that followed the same model fitting procedure as the analyses of joint agency ratings described in the next section. The analysis began with a maximal model that included a fixed effect of sequence type and a random intercept and slope for sequence type at the pair level, all of which were retained in the final model.

2.5.1.2 Joint agency ratings

We conducted two analyses to examine participants' joint agency ratings. We conducted these analyses using linear mixed-effects models, which allowed us to account for shared variance within pairs of participants. The first analysis compared participants' joint agency ratings between the two sequence types. This analysis included only a fixed effect of sequence type, and thus probed differences between sequence types without consideration of partners' synchronization performance. The second analysis included both sequence type and synchronization performance as predictor variables, so that we could simultaneously examine the effect of synchronization performance on joint agency ratings and confirm that participants reported stronger joint agency for musical duets than for constant pitch sequences at equivalent levels of interpersonal synchrony in each case. This analysis included fixed effects of sequence type, synchronization performance, and their interaction.

Each mixed-effect model analysis began with the relevant fixed effects and a maximal random effects structure (Barr et al., 2013; Bates et al., 2015). We estimated model fits using restricted maximum likelihood via the MIXED command in SPSS Version 26, and we refined the random effects as follows. First, if the model fitting procedure failed to converge, we removed random effects whose covariance was estimated as zero. Next, we used an iterative process to check whether the goodness of fit (-2 log-likelihood; -2LL) was significantly reduced after we removed the random effect that accounted for the least variance, using a likelihood ratio test. This procedure allowed us to remove random effects that were not supported by the data (Bates et al., 2015). Last, we tested whether goodness of fit significantly improved by fitting correlation parameters for the remaining variance components and for the residuals. Syntax for all mixed-model analyses is provided in the Supplementary Materials. For the analysis that compared joint agency ratings between sequence types, all random effects were retained in the final model. For the analysis of joint agency ratings as a function of both sequence type and synchronization performance, the final model included a random intercept and slope for the sequence type by synchronization interaction at the pair level; a random intercept and slopes for sequence type and synchronization at the participant level; and a random intercept at the trial level. For each final model, we report F-tests for fixed effects with degrees of freedom obtained by Satterthwaite approximation. We also report Cohen's d or standardized beta values as measures of effect size as appropriate.

2.5.2 Qualitative analysis of post-experiment interviews

We employed reflexive thematic analysis (Braun & Clarke, 2006, 2021) to examine participants' post-experiment interview responses. Our goal was to capture a rich overall description of participants' explanations of their ratings for each sequence type. We therefore used an inductive, data-driven approach rather than employing a pre-existing deductive framework, and we analyzed the data at a semantic level (i.e., we identified themes based on participants' explicit statements and did not attempt to infer or extrapolate the meanings of their responses; Braun & Clarke, 2006, 2021).

The four members of the research team worked together to develop and refine codes and identify themes within the dataset. We followed the six-step process outlined by Braun and Clarke (2006, 2021). First, to obtain a general familiarity with the data, each researcher read through one quarter of the 58 transcripts and highlighted responses related to joint agency for each sequence type. An initial codebook was then developed based on discussion of the highlighted responses. The codebook was then revised through an iterative process in which the four researchers separately coded a randomly selected set of transcripts (about 10 in total) and discussed any discrepancies until consensus was reached. Through this process, code definitions were clarified, new codes were identified, and potential themes were developed. Next, one researcher (Z.Z.) reviewed all of the transcripts to capture any remaining extracts. As a group we discussed any responses that were unclear or ambiguous. Responses were allowed to be assigned multiple codes; that is, if a participant's response fit two different codes, it was assigned both. The initial thematic map was then further developed and refined through an iterative process in which coded responses were organized into themes; each researcher independently checked whether the responses fit within their identified themes and subthemes; and the research team discussed both the coded responses and the overarching thematic organization. Note that codes and themes were identified based on the relevance of participants' responses with respect to our research questions rather than the frequency of any particular response, in keeping with Braun & Clarke's (2006, 2021) recommendations for reflexive thematic analysis (see Braun & Clarke, 2021, for further discussion of the relationship between frequency and meaning in thematic analysis approaches).[1]

3. Results

3.1 Quantitative analyses of experimental trials

First, we compared partners' synchronization performance between the two sequence types. As expected and as shown in the left panel of Figure 2, there was no significant difference in overall synchronization performance between the musical duets and the constant pitch sequences, $b = -0.02$, 95% CI [-0.05, 0.02], $F(1, 27.79) = 0.75$, $p = .39$, Cohen's $d = .08$. Next, we compared participants' joint agency ratings between musical duets and constant pitch sequences. As shown in the right panel of Figure 2, participants reported a significantly stronger sense of joint agency for musical duets than for constant pitches, $b = 0.60$, 95% CI [0.38, 0.83], $F(1, 27.27) = 29.70$, $p < .001$, Cohen's $d = 0.64$. Together, these findings provide initial support

[1]Separately from our main qualitative analysis, we also informally checked for any indication that participants had guessed the study's hypotheses by examining their responses to the first interview question ("Tell me what your experience was like doing this."). No participant reported guessing the hypotheses. Instead, participants typically commented on whether they enjoyed the task or how well they thought they performed.

for the hypothesis that participants would report stronger joint agency for musical duets than for constant pitch sequences, despite equivalent synchronization performance in both cases.

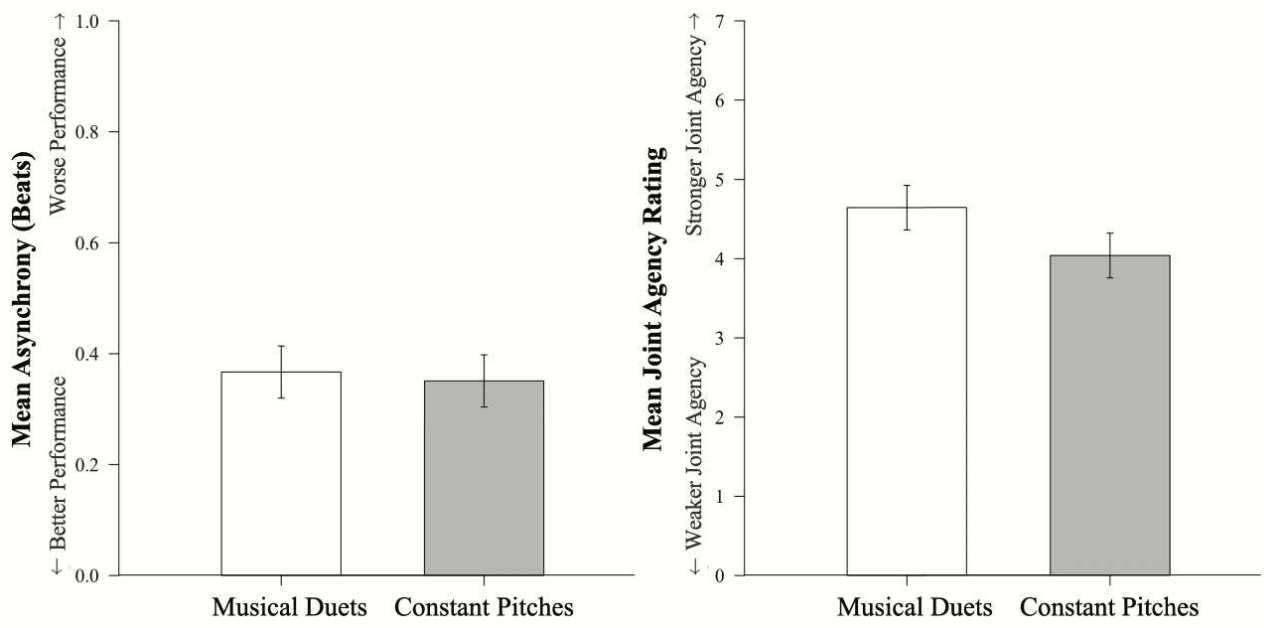

Figure 2. Synchronization performance (left panel) and joint agency ratings (right panel) for musical duets and constant pitch sequences. Error bars denote 95% CIs.

Last, we examined joint agency ratings as a function of both sequence type and synchronization performance, as shown in Figure 3. This analysis revealed that both main effects and their interaction were significant. The main effect of sequence type, $F(1, 225.82) = 77.68$, $p < .001$, indicated that joint agency ratings were higher for musical duets than for constant pitch sequences even after controlling for fixed and random effects of synchronization performance. The main effect of synchronization performance, $F(1, 51.63) = 152.52$, $p < .001$, indicated that, participants reported a stronger sense of joint agency on trials with better synchronization performance, consistent with previous research showing that interpersonal synchrony is an important cue to joint agency. However, these effects were qualified by a significant interaction between sequence type and synchronization performance, $F(1, 40.33) = 18.19$, $p < .001$. Simple slopes analyses confirmed that there was a significant effect of synchronization performance on joint agency ratings for both musical duets, $b = -3.87$, 95% CI [-4.48, -3.26], $t(73.59) = -12.69$, $p < .001$, $b^* = -0.96$, and for constant pitch sequences, $b = -2.57$, 95% CI [-3.16, -1.97], $t(40.33) = -4.27$, $p < .001$, $b^* = -0.66$. More importantly, post-hoc pair-wise comparisons of joint agency ratings between musical duets and constant pitch sequences, at asynchrony values ranging from 0.1 to 0.9 beats in increments of 0.1 beats[2], confirmed that musical duets elicited significantly stronger joint agency at asynchrony values up to and including 0.5 beats, Bonferroni-corrected ps $< .05$. However, the difference between musical duets and constant pitch sequences was no longer significant at asynchrony values of 0.6 beats or greater, Bonferroni-corrected ps $\geq .55$.

[2]Asynchrony values for post-hoc comparisons were selected so that they occurred at evenly spaced intervals, covered the range of asynchrony values in the dataset (values > 1 beat were rare, as reported in Section 2.5.1.1), and represented easily interpretable values (i.e., proportions of a beat).

Thus, this analysis confirmed that participants reported stronger joint agency for musical duets than constant pitch sequences on trials with equivalently good synchronization performance. However, there was no significant difference between sequence types for trials with equivalently poor coordination performance.

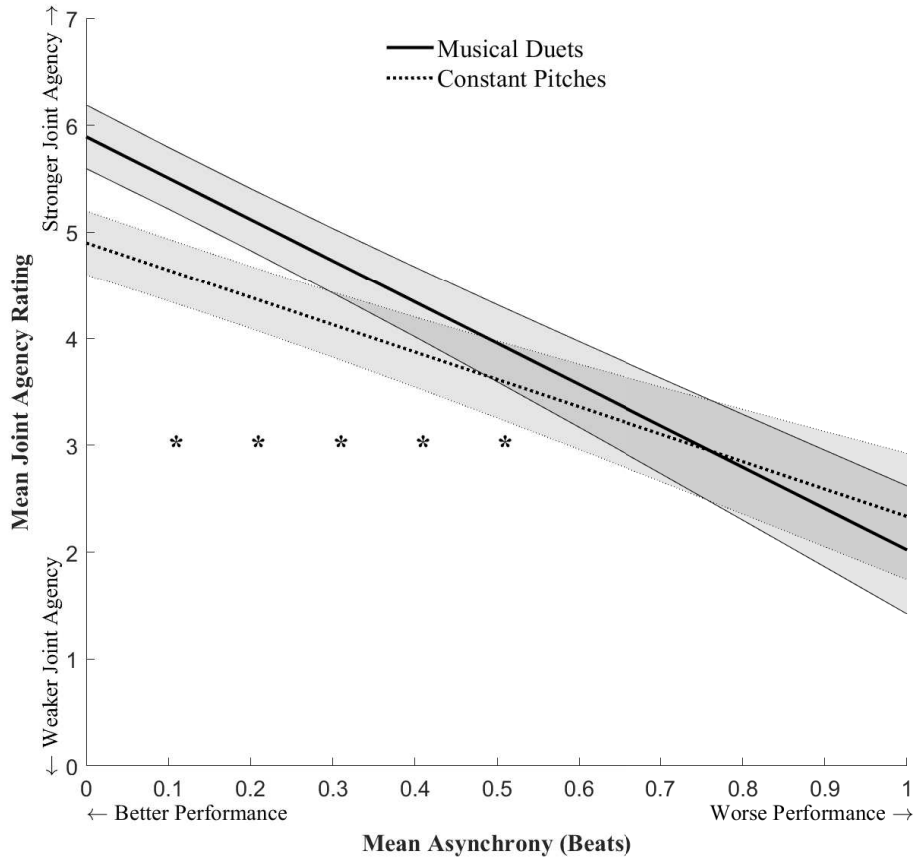

Figure 3. Estimated mean joint agency ratings by synchronization performance and sequence type. Shaded regions denote 95% CIs. Stars denote significant differences in joint agency ratings between musical duets and constant pitch sequences at specified asynchrony values.

3.2 Qualitative analysis of post-experiment interviews

Figure 4 illustrates the themes and subthemes compiled from participants' interview responses. As the figure shows, participants attributed the differences in their ratings between musical duets versus constant pitch sequences to their Knowledge of the Music, their Perceptions of Performance, the perceived Task Difficulty, and Task Enjoyability. We summarize each theme and its subthemes next.

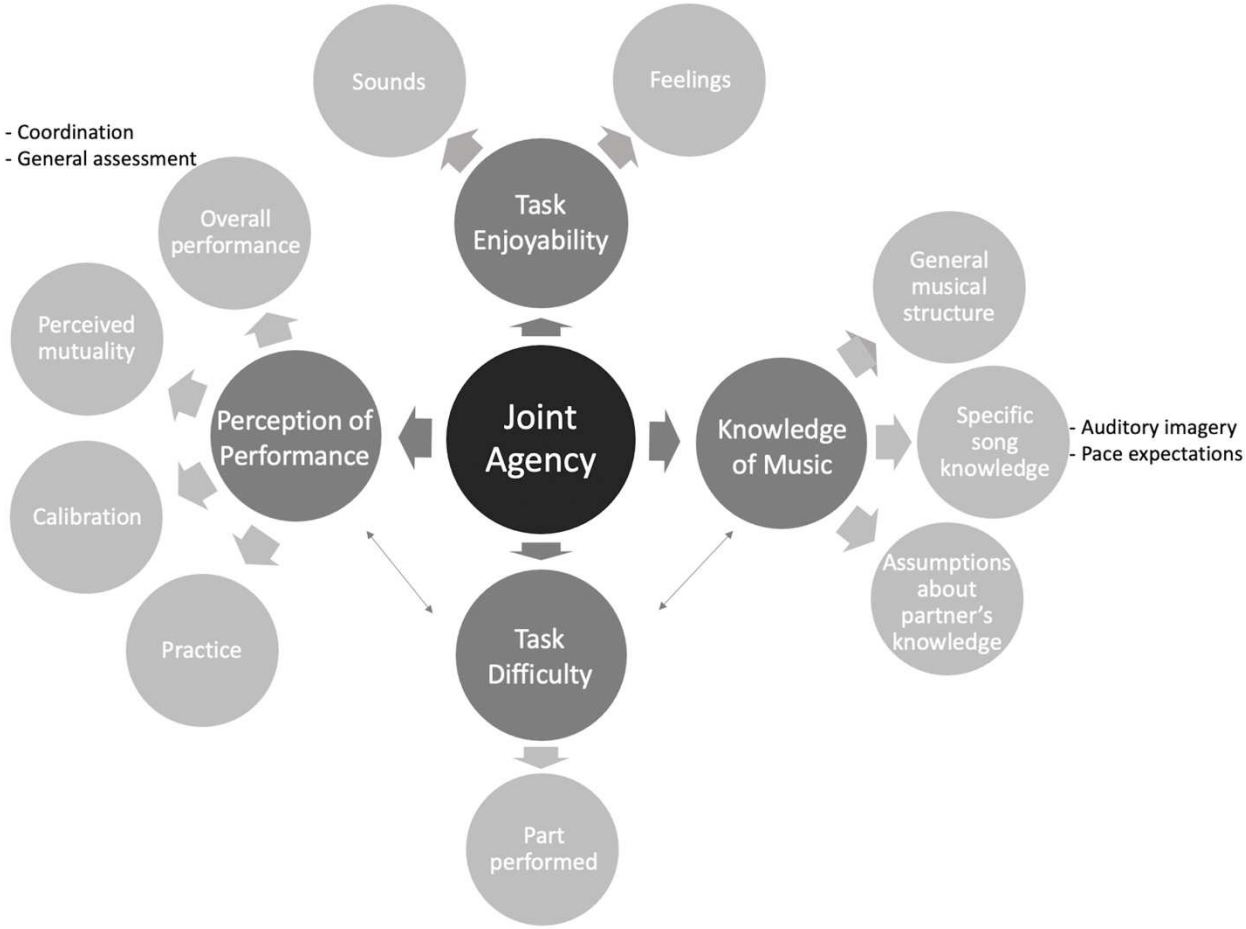

Figure 4. Visualization of themes and subthemes. Circle size, circle colour, thick arrows, and dashes are used to represent the structure of the themes and subthemes. Thin arrows denote links between subthemes.

3.2.1 Knowledge of Music

The first theme we will summarize is Knowledge of Music, represented on the right side of Figure 4. Within this theme, participants' comments indicated that they had a stronger sense of joint agency for the musical duets than for the constant pitch sequences because of their pre-existing knowledge about the duet music. People's comments about their knowledge of the music fell along three subthemes: General Musical Structure, Specific Song Knowledge, and Assumptions About the Partner's Knowledge.

3.2.1.1 General Musical Structure

Within this subtheme, participants attributed differences in their sense of joint agency between the two sequence types to the musical structure of the duets versus the comparative lack of structure of the constant pitch sequences. Some participants made general comments about the duets' structure, such as "there is kind of a template to go off of" and "it's built in almost". Other comments specifically mentioned the melody (e.g., the music "had a melody to it") or the rhythm

(e.g., "there was more rhythm to it").[3] Participants contrasted the musical duets with the constant pitch sequences, which they found to be "monotone" and "just repetitive, the same thing".

3.2.1.2 Specific Song Knowledge

Within this subtheme, participants reported that their sense of joint agency was partly influenced by their pre-existing familiarity with the specific songs that comprised the musical duets. For example, one participant said that "[the] musical duets have high ratings maybe because we are familiar with the songs rather than just the constant pitch". Some participants expressed that they used auditory imagery while performing the duets. For example, they described that they were "singing the songs", "try[ing] to hear the songs", or "play[ing] the lyrics" in their heads while coordinating with their partner. Some participants mentioned pre-existing knowledge of the speed or rhythm of the songs. For example, one participant stated that "you already know the musical duets, like you know the song already, and you have a pace that you're used to listening to it to, that's general for everybody that you learn from, hum, being a child. So when you spin it, like you already can expect what's to come". A subset of these participants mentioned that the speed or rhythm was included in their auditory imagery. Furthermore, some participants reported that their knowledge of the musical structure or the specific songs allowed them to predict what their partner would produce next, or when they would produce it, and adjust their own actions accordingly. Examples include the preceding quote regarding predictions based on the expected pace of the music, and "you can go, oh this is like what's supposed to happen next, and you are kind of moving your hand to that". Finally, some comments within this subtheme indicated that participants linked their knowledge of the music to their sense of joint agency via its facilitative effect on task performance. These comments will be discussed within the Task Difficulty theme presented below.

3.2.1.3 Assumptions About Partner's Knowledge

Within this subtheme, participants' comments extended beyond their own personal knowledge of the music to include assumptions about their partners' knowledge of the music. Some explicitly commented that they expected their partner to have specific knowledge of the songs. For example, one participant said, "I guess I expect them to know the song as well for the musical duet" and another said, "I think she knew the tones of the songs too". We also note here that many participants used the subject "we" in their comments within the Specific Song Knowledge subtheme described above (for example, "*we* all know [what] 'Mary Had a Little Lamb' sounds like" [emphasis added]). Some participants reported inferences about their partner's preferred speed: "I felt like I was trying to go my speed during what I thought the song was supposed to be like, and she was going her speed". One participant commented on their assumptions about their partner's musical background: "we're both different musically, so I may be musically inclined, and she may not be" and another participant commented on their assumptions about their partner's personal background: "I don't think she's from Canada…I don't think she knew [the songs]".

[3]We note here that references to rhythm likely reflect the metrical structure of the music (i.e., the alternation of strong and weak beats) rather than the rhythm itself (i.e., the pattern of note durations), because the musical duets and constant pitch sequences were constructed to have nearly identical rhythms (see Figure 1).

3.2.1.4 Summary of the Knowledge of Music Theme

In sum, participants reported that their sense of joint agency was strengthened by the structure and familiarity of the duet songs, which facilitated their ability to predict and adjust to their partners' actions, as well as by a sense that they and their partner shared common knowledge about the duet songs.

3.2.2 Perception of Performance

The second theme we will summarize is Perception of Performance, represented on the left side of Figure 4. Participants' comments within this theme indicated that they had a stronger sense of joint agency for the musical duets than for the constant pitch sequences because they perceived their performance to be better for the musical duets. People's comments about their perceptions of performance fell along four sub-themes: Overall Performance, Perceived Mutuality, Calibrating Ratings Based on Sequence Type, and Practice.

3.2.2.1 Overall Performance

Within this subtheme, participants indicated that their sense of joint agency was related to their general performance on the task. Some participants indicated that their joint agency ratings were specifically based on how well they synchronized with their partner. For example, one participant indicated that "[for] the constant pitches, I didn't feel as in sync with him as for the musical duets … there is more sync, definitely more in sync for [the duets]". Other participants indicated that they made their ratings based on a more general assessment of performance. For example, one participant attributed their stronger sense of joint agency in the duet condition to their perception that "we were doing better with the musical duets than the pitches".

3.2.2.2 Perceived Mutuality

Some participants attributed their joint agency ratings to a sense of mutual adaptation with their partner when producing musical duets compared to a sense of independent performance when producing constant pitch sequences. For example, one participant said, "'cause I know that she was trying to match my beat, and I was trying to match hers, so I knew there was some sort of connection going on" to explain their stronger sense of joint agency for the musical duets. The same participant contrasted the duets with the constant pitches, saying "But when it's just that - constant pitches, it just felt more like a computer than I was doing a duet with her." Similarly, another participant said that in "the constant pitches, we were kind of solo" and another mentioned that "I felt like we were totally separate a lot of the times on the constant pitches".

3.2.2.3 Calibrating Ratings Based on Sequence Type

Some participants reported that different performance criteria influenced their sense of joint agency for the two sequence types. Typically, participants reported a more lenient criterion for the musical duets than for the constant pitches. For the constant pitches, for example, one participant stated that "even if they are coordinated, I personally would not perceive them to be coordinated, to [the same] extent as compared to a musical duet". Whereas for the musical duets, participants made statements such as, "it can be close enough and still sound good" and "I was thinking we were doing really really good even if we were off a little bit" so "I was grading us on an easier curve".

3.2.2.4 Practice

Some participants indicated that they felt that they did not perform well at the beginning of the experiment. However, after several trials of practice, they "started to get used to it", felt their performance improved, and therefore "felt more connected" with their partner.

3.2.2.5 Summary of the Perception of Performance Theme

In sum, participants reported that task performance was an important cue to their sense of joint agency. Moreover, they reported that the influence of task performance went beyond simple synchrony of tones onsets and additionally included feelings of mutuality versus independence and perceptions of performance relative to sequence-specific criteria.

3.2.3 Task Difficulty

A third theme within participants' interview responses was Task Difficulty. Participants' comments within this theme related their sense of joint agency to their perception that one condition was easier or harder than the other. Almost all participants who mentioned task difficulty in their interview found it easier to perform musical duets than constant pitch sequences. Typically, participants attributed the ease of performing musical duets to factors already discussed in the Knowledge of Music and Perception of Performance themes, as represented by thin arrows linking these themes to Task Difficulty in Figure 4. For example, with respect to Knowledge of Music, participants reported that it was easier to perform the musical duets because the duet "had a melody to it" (General Musical Structure); because they were "familiar with most of the songs" (Specific Song Knowledge); or because they and their partner "both have a background of it" (Assumptions About Partner's Knowledge). Participants reported that the General Musical Structure or their Specific Song Knowledge made it easier to "get into the rhythm," to "keep up or slow down if you need to," to "sync up", or to "match up" the melody with the accompaniment. Conversely, people indicated that the lack of structure in the constant pitch sequences made them more challenging to perform: "the constant pitches, I found really difficult 'cause I didn't have anything to go off of. At least the musical duets, I could hear the song. But the constant pitches, it was just the sound". With respect to Perception of Performance, participants reported that they could better adapt to each other to match up their parts in the musical duets (Perceived Mutuality); that the musical duets were easier because they could "still sound good" even with a slightly unsatisfactory performance (Calibrating Ratings); or simply that it was "easier to coordinate" the musical duets than the constant pitches (Overall Performance).

As shown in Figure 4, some comments within the Task Difficulty theme fell into a subtheme labeled Part Performed. Participants' comments within this subtheme indicated that their sense of joint agency differed when they played different parts of the musical duets or constant pitches (i.e., the melody vs. accompaniment or higher vs. lower pitches). Participants mainly expressed that they found it easier to hear the melody or higher pitches and had a harder time "picking out" the accompaniment or lower pitches. For example, one participant linked the ease of performing the melody to their specific song knowledge: "[the melody is] what everyone knows, or at least what I know most about those songs, so the accompaniment was a little bit more difficult because I kept on getting lost in the melody". Other participants specifically mentioned that the constant pitch sequences were harder because they had difficulty keeping track of which part they were performing. For example, one participant said that "with the constant pitch, I at some point, I forgot which one was mine, it was either high pitch or the low

pitch. … So I think that's why it's kind of hard to do that one." These comments suggest a link between participants' joint agency ratings and their sense of individual self-agency, a point to which we return in the Discussion.

Finally, within the Task Difficulty theme, a few participants said that they found it easier to perform the constant pitch sequences than the musical duets. These participants attributed the ease of performing the constant pitches to only needing to consider the timing of the notes instead of also needing to align the musical structure of the duets. For example, one participant said, "I found it easier when … we were just trying to, like, line up with the constant pitches than to, like, try to complement the melody and the harmony."

3.2.3.1 Summary of the Task Difficulty Theme

In sum, participants reported a close link between their sense of joint agency and the ease of task performance, and they attributed ease of task performance to aspects of their musical knowledge, their task performance, and their sense of self-agency.

3.2.4 Task Enjoyability

The fourth theme in participants' interview responses was Task Enjoyability. Participants' comments within this theme related their sense of joint agency to how pleasant it was to perform each sequence type, with respect to either the sounds that were produced or the feelings they experienced.

3.2.4.1 Pleasant Versus Unpleasant Sounds

Comments within this subtheme related the sense of joint agency to the pleasing sounds of the duets (e.g., they were perceived as "more beautiful," "soothing to the ear," or "sound so nice") compared to the constant pitch sequences, which were just "like ticking noises."

3.2.4.2 Pleasant or Unpleasant Feelings

Comments within this subtheme related the sense of joint agency to pleasant feelings when producing the duets, such as finding the duets to be "a lot more comfortable," "more interesting," and "encouraging," and having "enjoyed [the duets] better". As one participant put it, "I felt more comfortable and connected with my partner on the musical duets one."

3.2.4.3 Summary of the Task Enjoyability Theme

In sum, people reported that they felt stronger joint agency for the musical duets than for the constant pitch sequences because the duets created more pleasant sounds and feelings.[4]

4. Discussion

The current study examined whether relations between partners' actions influence the sense of joint agency, in joint actions that require precise interpersonal synchrony, above and beyond the degree of synchrony partners achieve. The current study also examined the broader set of cues that influence joint agency during such joint actions. Pairs of participants produced synchronized tone sequences together, which entailed either a simple temporal alignment relation between partners' actions (each person produced a series of unchanging pitches and participants'

[4]Participants' post-experiment ratings of how good it felt to play each type of sequence provide further evidence that they found the musical duets more pleasant than the constant pitches, as the former were rated higher than the latter (M for musical duets = 7.28, SD = 1.27; M for constant pitches = 4.81, SD = 1.33; $t(57) = 11.05$, $p < .001$).

goal was to synchronize tone onsets) or additionally included more complex metrical and harmonic relations between partners' actions (partners produced musical duets comprised of familiar melodies and accompaniments). As expected, participants reported stronger joint agency when they produced sequences with richer metrical and harmonic relations compared to when they produced sequences with only a simple temporal alignment relation. This was true when comparing trials in which partners achieved equivalently good synchronization performance for each sequence type, although there was no significant difference in joint agency when comparing trials in which partners achieved equivalently poor synchronization performance for each sequence type. Furthermore, post-experiment interviews revealed that a variety of cues influenced participants' sense of joint agency, including their knowledge of the music, their perceptions of how well they performed the task, the perceived difficulty of the task, and the perceived enjoyability of the task. We next consider the quantitative and qualitative results together to outline the study's major findings.

A first major finding is that our quantitative and qualitative results converge to support the hypothesis that relations between partners' actions influence the sense of joint agency in joint actions that require precise interpersonal synchrony, above and beyond the degree of synchrony partners achieve. Our quantitative results confirm that participants report stronger joint agency for musical duets that entail richer metrical and harmonic relations between partners' actions than for constant pitch sequences that entail a simple temporal alignment relation between their actions, when comparing trials with equally good synchronization performance for each sequence type. Our qualitative results provide corroborating evidence that people are sensitive to the relations between partners' actions in musical duets compared to constant pitch sequences: Participants attributed differences in joint agency between sequence types in part to the requirement that they "match up" or "complement" the melody with the accompaniment in the musical duets, which they contrasted with the simpler requirement of aligning "just the sound[s]" in the constant pitch sequences. Together, these findings complement previous research showing that relations between partners' actions influence their sense of joint agency in joint actions that do not require precise interpersonal synchrony (Le Bars et al., 2020a, 2020b). These findings also have implications for our understanding of how representations of joint action influence joint agency, a topic we discuss further at the end of the Discussion.

A second major finding from the current study is that our quantitative and qualitative results converge to support the conclusion that synchronization performance is also an important cue to joint agency. Our quantitative results confirm that people report stronger joint agency for trials with better synchronization performance, for both musical duets and constant pitch sequences. Our qualitative results corroborate this finding, because participants report that the perceived degree of synchrony or coordination they achieved influences their sense of joint agency. These findings align with previous research demonstrating that synchronization performance in particular (Christensen et al., 2022; Reddish et al., 2020) and coordination performance in general (e.g., Bolt et al., 2016; Dell'Anna et al., 2020) have a strong influence on people's sense of joint agency. Interestingly, participants' intuition was that they achieved better performance for musical duets than for constant pitch sequences, and they attributed their stronger sense of joint agency for musical duets to that difference in performance. Participants' intuitions differed from our quantitative results, which showed that overall synchronization performance was similar between the two sequence types and that ratings of joint agency were higher for musical duets than constant pitch sequences when comparing trials with equally good performance. One possibility is that participants' intuitions might reflect a salient contrast

between trials in which they achieved relatively good synchronization (and experienced stronger joint agency for musical duets) versus trials in which they achieved poor synchronization (and, statistically, reported no difference between duets and constant pitches). We note here, then, the value of systematic manipulations that allow researchers to isolate the effects of specific cues and elucidate how these cues combine to inform participants' sense of joint agency. Nevertheless, complementing such manipulations with participants' reports provides a richer understanding of how each cue impacts joint agency, as we illustrate in the next several paragraphs.

First, participants' reports provide a richer understanding of how relations between partners' actions and synchronization performance influence joint agency. With respect to relations between partners' actions, participants' comments reveal that it is not only the structural relations between the parts of a musical duet (i.e., the alignment of the melody and accompaniment, which creates metrical and harmonic relations) that strengthen their sense of joint agency. Rather, people report that their knowledge of the specific songs they performed and their assumptions about others' knowledge of those songs also contribute to stronger joint agency for duets compared to constant pitches. The latter finding points to an influence of mentalizing (i.e., attributing knowledge, beliefs, or mental states to one's action partner; Frith, 2012; Wu et al., 2020) on joint agency. Further research is needed to more fully investigate the impact of mentalizing on joint agency, which would complement recent work that has investigated the impact of mentalizing on individual self-agency in social contexts (e.g., Beyer et al., 2017; Beyer et al., 2018; Ciardo et al., 2020; Sidarus et al., 2020). People further report that their general and specific song knowledge influence joint agency by facilitating their ability to predict and adjust to their partners' actions. This finding aligns with research showing that people develop schematic knowledge of the relations between individual parts of a musical duet, which they use to predict upcoming events in each part (Palmer & Jungers, 2003), and that this predictive ability is enhanced when the music is familiar (Huron, 2006). This finding also aligns with previous theoretical work and empirical evidence that joint agency is strengthened when a partner's actions and the overall joint outcome are more predictable (Bolt & Loehr, 2017; Pacherie 2012). We note here, however, that we strove to ensure that both sequence types were equally predictable, by using familiar melodies in the musical duets condition (which allowed participants to predict which pitch would be elicited at each beat in the sequence) and a series of constant pitches (in which the pitches were always the same and thus were perfectly predictable). Indeed, if anything, musical duets might have been *less* predictable because participants likely were not familiar with the specific accompaniments we composed for the study. Participants nevertheless perceived that the duets were more predictable and that this impacted their sense of joint agency.

In a similar vein, participants' comments regarding how their perceptions of performance influence their sense of joint agency reveal that it is not "just" the degree of synchrony or coordination they objectively achieve that impacts joint agency. Rather, people additionally report that perceived task difficulty and task success influence joint agency, which converges with previous findings that metacognitive judgments of performance are a central cue to agency in both solo (Metcalfe et al., 2012; Metcalfe et al., 2013) and joint action contexts (van der Wel, 2015). People also report that different performance criteria influence their ratings of joint agency for musical duets compared to constant pitch sequences, with less precise synchronization required to elicit joint agency for musical duets. These comments could reflect an influence of schematic expectations on the sense of joint agency, as mentioned in the

preceding paragraph, and/or the presence of response biases that might need to be accounted for in future studies of explicit judgments of joint agency (see Loehr, 2022, and Zapparoli et al., 2022, for further discussion of explicit versus implicit measures of agency in joint action). Together, these findings underscore the value of adopting a mixed-methods approach, which here revealed additional influences of participants' subjective perceptions of sequence predictability and task performance on joint agency that would not otherwise have been evident using only a quantitative experimental paradigm that objectively equated the experimental conditions along these dimensions.

Finally, participants' post-experiment interviews also identified an additional cue that was not otherwise captured in our quantitative measures, namely, task enjoyability. Specifically, people reported that they felt stronger joint agency for musical duets than for constant pitch sequences because the duets created more pleasant sounds and elicited more pleasant feelings. This finding aligns with Stephens' (2020) ethnographic study showing that when people sing together in a large community choir, their dynamic perceptions of how well their voices are integrated contribute to an ebb and flow of joint agency accompanied by positive and negative emotional responses. This finding also aligns with Noy et al.'s (2015) finding that joint agency may induce a heart rate response related to task enjoyment. Together, these findings support a potential link between joint agency and social bonding that has been proposed by other researchers (Zapparoli et al., 2022), whereby the positive emotions that accompany joint agency might transfer to subsequent interactions in the form of enhanced pro-social behaviour or strengthened social bonding (see also Rabinowitch & Gill, 2021). That said, further research will be needed to clarify the direction of causality between joint agency and positive emotions, that is, whether experiencing a sense of joint agency elicits positive emotions or vice versa.

Taken together, findings from the current study support the hypothesis that multiple cues influence the sense of joint agency in joint actions that require precise interpersonal synchrony. These findings align with research indicating that multiple cues influence joint agency in joint actions that do not rely heavily on interpersonal synchrony (Loehr, 2022; Zapparoli et al., 2022). Further work will be needed to determine whether and how these cues are differentially weighted depending on the joint action context, as posited by cue-integration models of solo and joint agency (Moore & Fletcher, 2012; Synofzik et al., 2013; Zapparoli et al., 2022). Findings from the current study also shed light on three additional issues related to the sense of agency in joint action. First, participants' post-experiment interview comments substantiate previous work that has considered 'independent agency' to be one possible form of joint agency (see, e.g., Dell'Anna et al., 2020; Loehr, 2022). Specifically, participants' comments provide evidence that people sometimes experience joint agency as a sense of working independently toward the shared goal of a joint action, as reflected in comments indicating that they felt "totally separate a lot of the times" or "more like a computer than I was doing a duet with her." Second, participants' comments reflected the multiple aspects of joint agency delineated by Saint-Germier et al. (2021), including the *outcome-oriented* aspect (i.e., a sense of contributing together to a joint outcome, reflected in, e.g., participants' comments concerning their sense of mutual adaptation) and the *integration-oriented* aspect of joint agency (i.e., a sense that actions are part of a meaningful whole, reflected in comments indicating that the musical duets were more pleasant, beautiful, soothing, and interesting than the constant pitches). This finding suggests that the visual analog scale used here may be particular useful for examining the sense of joint agency encompassing all of its multiple aspects. However, further work is also needed to examine convergence between the broad scale employed in the current study and scales that

capture individual aspects of joint agency (such as scales that focus specifically on control, as employed by Bolt et al., 2016 and Dell'Anna et al., 2020, or scales that focus specifically on the outcome- or integration-oriented aspects, as employed by Saint-Germier et al., 2021). Rating scales used to date have been developed based on researchers' evolving conceptual understanding of the sense of joint agency. Participants' post-experiment interviews in the current study provide converging evidence in support of this understanding, as just described, and further examination of whether these scales converge with each other (and with implicit measures of agency such as intentional binding or sensory attenuation) could contribute to further refinement of this conceptual understanding. Last, participants' comments provide some evidence that people perceive a link between joint agency and individual self-agency. Specifically, a few participants reported that they experienced a reduced sense of self-agency (i.e., getting "lost" or forgetting which part they were playing) when asked to comment on their sense of joint agency. This finding aligns with ongoing work investigating the relationship between joint and self-agency and the factors that modulate it (see, e.g., Christensen et al., 2022; Le Bars et al., 2020a, 2020b), which is also a topic of ongoing theoretical development.

Finally, we return to one of the primary questions motivating the current study and speculate briefly about *why* relations between partners' actions influenced joint agency in the current study. As noted in the Introduction, representations of joint action entail both a collective level (the shared goal of a joint action) and an individual level (own and partners' contributions to the shared goal). This multi-level structure is reflected in hierarchical predictive models of joint action (Keller et al., 2016; Pesquita et al., 2018), which include a dynamic representation of the shared goal as well as parallel predictive models for one's own and partners' actions. Zapparoli et al. (2022) propose a theoretical model in which joint agency arises when processes related to one's own and partners' actions are weighted approximately equally within such a hierarchical predictive model. In other words, the strength of joint agency is determined by the relative weighting of individual actions. We suggest here an alternative possibility, that the strength of joint agency might instead reflect the relative weighting of the collective-level shared goal relative to individual action goals. Specifically, in the current study, the shared goal might have received a higher weighting relative to individual action goals when people produced musical duets, because their richer metrical and harmonic relations create a more compelling joint outcome. In contrast, the shared goal might not have received a higher weighting relative to individual action goals when people produced constant pitch sequences, because the simple temporal alignment relation did not create as compelling a joint outcome. A higher weighting of the shared goal relative to individual goals might thus have elicited a stronger sense of joint agency when people produced duets, whereas a less increased weighting of the shared goal relative to individual goals might have elicited a weaker, more independent sense of joint agency when people produced constant pitch sequences. Such an account could potentially explain why other studies did not show differences in joint agency between experimental conditions, if their experimental manipulations did not affect the weighting of the shared goal relative to individual goals. For example, Christensen et al. (2022) found no difference in joint agency between conditions in which participants produced musical duets that differed only in terms of the pitch distance between melody and accompaniment, but were identical in terms of the metrical and harmonic relations between them. Alternatively, such findings could indicate that joint agency is influenced by retrospective cues (i.e., the perceived pleasantness of the joint outcome) rather than prospective cues (weighting of action representations). Further work that manipulates the weighting of action representations while holding the joint outcome constant (e.g., by

manipulating the salience of individual vs. shared goals) could be useful to arbitrate between these potential explanations. In a similar vein, further work could investigate the generalizability of the current findings to other types of relations between partners' actions, such as the relative effort, difficulty, or pivotality of each partner's contributions to the joint action.

5. Conclusions

In sum, findings from the current study further our understanding of the sense of joint agency that arises when people perform joint actions together. Specifically, the current study provides evidence that the relations between partners' actions influence the sense of joint agency, above and beyond the degree of synchrony partners achieve, even in joint actions that require precise interpersonal synchrony. The current study also provides evidence that multiple additional cues also contribute to people's sense of joint agency for such joint actions, including the degree of synchrony they achieve, their metacognitive judgements about the quality of their performance, and their pre-existing knowledge (and mentalizing about others' knowledge) of the shared goal of the joint action. These findings suggest several interesting avenues for future research, including how different cues to joint agency are weighted in different joint actions contexts and whether and how the strength of joint agency relates to mental representations of shared and individual goals within a joint action.

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Figure Captions

*Figure 1***.** (A) Schematic diagram of the experimental set-up. Circles represent electronic music boxes and arrows indicate direction of rotation. (B) Example musical duet (top staff: melody; bottom staff: accompaniment). (C) Example constant pitch sequence (top staff: higher-pitch part; bottom staff: lower-pitch part).

Figure 2. Synchronization performance (left panel) and joint agency ratings (right panel) for musical duets and constant pitch sequences. Error bars denote 95% CIs.

Figure 3. Estimated mean joint agency ratings by synchronization performance and sequence type. Shaded regions denote 95% CIs. Stars denote significant differences in joint agency ratings between musical duets and constant pitch sequences at specified asynchrony values.

Figure 4. Visualization of themes and subthemes. Circle size, circle colour, thick arrows, and dashes are used to represent the structure of the themes and subthemes. Thin arrows denote links between subthemes.

Appendix
Joint Agency Rating Scale and Post-Experiment Interview Questions

Figure A1

Joint Agency Rating Scale

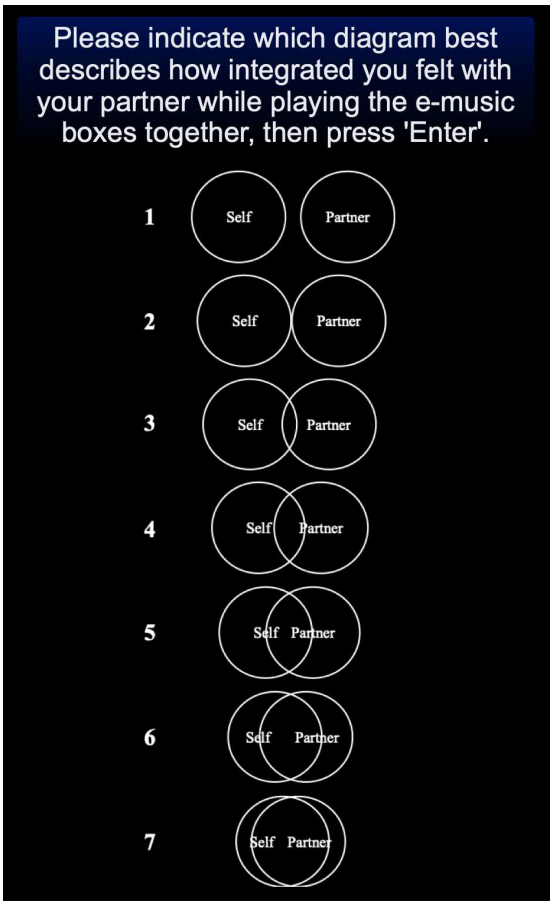

Figure A2

Post-Experiment Interview Questions

1. Tell me what your experience was like doing this.
2. After showing and explaining participants' ratings: These are your ratings when you played music and when you played a series of tones. What do you think about this?
3. Can you tell me more about what you mean? OR As you can see, your ratings between the two conditions are different. We are trying to understand why these are different. What is your explanation for this?
4. Example questions that could be asked depending on participants' ratings:
   a. You rated a lot of 2s in the constant pitches condition. Can you tell me more about why you think you made this rating?
   b. You rated a lot of 6s in the music duets condition. Can you tell me more about why you think you made this rating?
5. How good did it feel when you were playing the music duets condition, on a scale from 1-10?
6. How good did it feel when you were playing the constant pitches condition, on a scale from 1-10?
7. Is there anything else you would like to say about how you were feeling during the musical duets condition compared to the constant pitches condition?