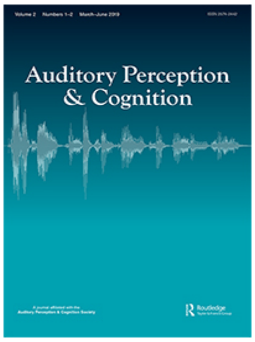

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Hand Shape Familiarity Affects Guitarists' Perception of Sonic Congruence

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ABSTRACT
Musical performance depends on the anticipation of the perceptual consequences of motor behavior. Altered auditory feedback (AAF) has previously been used to investigate auditory-motor coupling but studies to date have predominantly used MIDI piano in experimental tasks. In the present study, we extend the AAF paradigm to the guitar, which differs from the piano both motorically and in its pitch-to-place mapping, allowing further investigation into the nature of this coupling. Guitarists played chords on a MIDI guitar in response to tablature diagrams. In half of the trials, one of the notes in the heard chord was artificially altered. Participants judged whether the feedback was altered or not, responding as quickly and accurately as possible by pressing one of two buttons on a footswitch. Participants ranked the familiarity of the chord shapes and the hand shapes of the stimuli. Judgement of sonic congruence was faster when the chord and hand shape were familiar, and when feedback was congruent, though there was no interaction between these factors. Our findings suggest that guitarists' auditory-motor coupling is heterogenous with respect to their technique, and that perception-action coupling operates at the abstract level of the gesture. We discuss implications of these findings with regard to forward models and embodiment.

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Forward models; altered auditory feedback; auditory-motor coupling

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Musical performance involves complex coordination between motor control and its intended action-effects. Because auditory feedback is too slow to be used as the sole means of online error correction, the perceptual consequences of sound-producing musical gestures must be anticipated via forward models, the process by which the anticipated sensory consequences of actions are simulated in the brain in conjunction with generating movements (Maes, Leman, Palmer, & Wanderley, 2014). The development of the link between motor behavior and intended sound is part of what constitutes musical skill. These associations have been probed in previous experiments. D'Ausilio, Altenmüller, Olivetti Belardinelli, and Lotze (2006) used transcranial magnetic stimulation (TMS) to show increased motor excitability in pianists while listening to a rehearsed

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piece compared to a non-rehearsed one. This is consistent with evidence from an fMRI study showing greater coactivation when participants listened to practiced note-sequences in comparison to the same notes in different sequences, and to melodically similar but motorically unknown pieces (Lahav, Saltzman, & Schlaug, 2007).

Behavioral studies also reveal a bidirectional coupling between sound and movement. Drost, Rieger, Brass, Gunter, and Prinz (2005a) required pianists to play individual chords in response to imperative visual stimuli with concurrent task-irrelevant auditory stimuli, which were either congruent or incongruent with the played chords. Response times were slower in the incongruent condition. The disruptive effect of incongruent task-irrelevant stimuli, which represent potential action effects, was also found for two-tone sequences (Drost, Rieger, Brass, Gunter, & Prinz, 2005b).

Although the results of the TMS and fMRI studies suggest that the strength of auditory-motor coupling is greater for musical materials that have been practiced, questions remain about the level of abstraction at which this coupling operates. Drost, Rieger, and Prinz (2007) investigated this question in a comparison of the disruptive effects of task-irrelevant incongruent auditory stimuli on auditory-motor coupling between pianists and guitarists. They found that the disruptive effects only occurred when the incongruent stimuli had the same timbre as the instrument played, indicating that auditory-motor coupling does not operate solely at the level of abstract musical attributes such as major/minor tonality. Further evidence in support of this comes from a study showing that beatboxers and guitarists selectively engaged sensorimotor regions when listening to the instrument they can play (Krishnan et al., 2018). In a study with pianists, Novembre and Keller (2011) had participants imitate silent videos of chord sequences on a keyboard without auditory feedback. Their result that imitation was fastest when target chords were congruent with the harmonic context indicate that higher-level musical features do indeed play a role in perception-action coupling.

While these studies all demonstrate that perception-action coupling operates at abstract levels, the relationship between different movements that can produce similar sounds remains relatively unexamined. This question raises important topics for further experimental inquiry. One possibility is that musicians have trained on their instruments so much that they have developed a veridical mapping from an auditory image of the sound to be produced and an abstract representation of pitch-triggering events on their instrument. For example, a pianist might have the sound of a chord in mind, which maps to a pattern of notes on the keyboard in a way that does not depend on the particular movements or fingers used to play it. In contrast, auditory-motor coupling could be at the level of musical gestures, such that musical training links a particular set of multiple different movements (such as would be used to play a phrase or chord) to a similar auditory action-effect (e.g., different fingerings on the guitar that produce the same sound). This view has some support from the theoretical perspective of embodied cognition (Amsel, Urbach, & Kutas, 2014; Barsalou, 2008; Gentsch, Weber, Synofzik, Vosgerau, & Schütz-Bosbach, 2016; Pulvermüller, 2013), which places special emphasis on the common representational domain of movement and perception. Such a possibility is also compatible with bidirectional auditory-motor mapping, such that anticipatory auditory images of tones and chords are linked to the movements used to enact them, and vice versa (Maes et al., 2014).

Further, regarding musical gesture, there are studies that show that expertise on an instrument affects perceptual sensitivity to musical gesture in the audio-visuomotor domains. Proverbio, Attardo, Cozzi, and Zani (2015) found that violinists and clarinetists who had more expertise on their instrument were less likely to miss audiovisual incongruences (e.g., hand movements out of sync with audio playback) when tasked with looking for them in video playback of violin or clarinet performances, respectively. If instrumental expertise is a factor in perceptual sensitivity of musical gesture, the guitar offers a unique way of looking at the perception-action coupling. Aside from the lowest and highest parts of the range on a guitar in standard tuning, notes have several different locations on the guitar where they can be played. As an example, the note E3 can be played on the 2nd fret of the D string, 7th fret of the A string, or the 12th fret of the E string. As such, the guitar offers multiple locations for playing the same quality chord on the fingerboard using different hand shapes, playing the same chord voicing (i.e., an ordered selection of the set of notes for that chord) on the fingerboard using different hand shapes, and playing different chords on the fingerboard using the same hand shape.

Contrasting the two models (veridical pitch-to-place mapping versus musical gestures) suggests that perception-action coupling might occur on multiple levels of abstraction, where veridical mapping and musical gestures work at different levels within the process. Veridical mapping contributes to the pitch-to-place mapping, while the musical gesture model maps hand movements to expected sound. As such, the guitar is the ideal instrument to compare veridical mapping to musical gesture because while any given chord voicing does map to the fret board in specific pitch-to-fret ways, it can do so in *multiple* ways allowing for the different hand gestures used to play a given chord voicing to be dissociated from the pitches produced. Through use of altered auditory feedback (AAF) in the current study, we can parse the veridical mapping from the musical gesture contributions to perception-action coupling on the guitar, thus gaining more insight as to the nature of the perception-action coupling.

Auditory-motor coupling has been investigated using AAF paradigms in which the expected sensory result of an action is artificially manipulated in order to probe the action-effect representation (Furuya & Soechting, 2010; Maidhof, Vavatzanidis, Prinz, Rieger, & Koelsch, 2010; Pfordresher, Mantell, Brown, Zivadinov, & Cox, 2014). These studies have demonstrated perception-action coupling by disrupting the auditory feedback in terms of timing, velocity and/or pitch of musical notes as participants played, and observing disruptions to their musical performance. It should be noted that all of these studies use MIDI piano keyboards, which have a one-to-one mapping of keys to pitches with a left-right association with pitch height. While this is not a problem in principle for these experimental designs, it would be desirable to extend the paradigm to other instruments in order to expand the possible types of experimental remapping of movement to sound, such as the many-to-one mappings possible on the guitar as we have noted. Using instruments besides the piano is not a trivial extension of this research program. Rather, perception-action coupling may operate at different levels of abstraction on different instruments like the guitar, wind instruments, or string instruments. Such variation would be important to consider theoretically, and it cannot be investigated without bringing these instruments into an experimental setting.

The present experiment extends the AAF paradigm to the guitar in order to exploit its many-to-one mapping of fingerboard locations to pitches, a feature that is not possible to investigate at the piano where a given pitch can only be produced by a single key and single physical location at the instrument (one key, one pitch). This allowed us to investigate auditory-motor coupling at the level of musical gesture, by varying the hand shape used to play the same-sounding chord in two different locations on the guitar. Although it is technically possible to vary the hand shape to play a given chord on the piano, this can result in using the hand in ways that would not usually arise in a playing context (Novembre & Keller, 2011). In contrast, on the guitar it is possible to use a hand shape usually associated with a given chord and a less familiar hand shape for the same-sounding chord, which is still ecologically valid. We investigated whether the familiarity of the hand shape used to play a chord (as assessed for each individual participant) affects participants' sensitivity to altered feedback as measured by their ability to detect artificially-induced incongruencies to the auditory feedback of their playing. If familiarity with the hand shape produces stronger anticipatory auditory images, this would suggest that musicians' perception-action coupling is not due to a mere, homogenous pitch-to-place map between a particular fret and a particular note, but rather operates at the more abstract level of particular gestures (i.e., the guitarists' hand configurations). We hypothesized that familiarity with movements used to play particular chords would indeed aid judgements of the veridicality of the feedback. Further, given that altered feedback alone can disrupt the ability to evaluate its veridicality (regardless of gestural familiarity), we investigated whether these disruptive affects were stronger in the case of familiar gestures; if unfamiliar gestures have weaker anticipated feedback, the disruptive effects of incongruence should be smaller since the anticipated sound against which the exogenous feedback is compared is weaker (i.e., there should be an interaction between auditory feedback congruence and familiarity).

Method

Participants

Participants (N = 21, 19 males, 2 females; mean age = 26.52, SD = 9.00 years) were all guitarists without absolute pitch (according to participants' self-reports) who played right-handed and were university/conservatory students or professionals in the Manchester and Leeds areas. Participants were recruited via correspondence between college faculty members and potential volunteers, and snowball sampling of Manchester and Leeds musicians. None of the participants were compensated in accordance with the university's ethics policies. All participants gave informed consent. Each participant completed a short questionnaire including demographic information and estimates of musical experience, and the short form of the Edinburgh Handedness Inventory. To quantify musical experience, the total hours of playing was estimated using the method of Pinho, de Manzano, Fransson, Eriksson, and Ullén (2014), which asks participants to estimate the number of hours per week spent playing in three different age ranges (11 and under, between 12–17, and 18 and older). The sum total experience for our participants was M = 11,695.05 hours, SD = 10,382.07 hours. We did not ultimately include this variable in our models, however, because we were interested in differences within participants, relative to their own ratings of familiarity of the stimuli. As for handedness, all participants played the guitar right-handed (i.e., the right hand strums the strings), though 2 participants were left handed, and 3 were ambidextrous according to their handedness score.

Stimuli

The imperative visual stimulus in each trial was in the form of a tablature diagram depicting one of 16 possible guitar chords as in Figure 1. We designed 8 pairs of tablature diagrams. Each pair had two diagrams that produced the same sounding chord, but with two different fingerings. One of the fingerings was very familiar and common, and the other was not and was thus unfamiliar. One such pair is depicted in Figure 1. While the authors relied upon their own guitar-playing expertise to choose certain chords to be unfamiliar, it could have been that some participants happened to actually be familiar with them, so for our analysis, we relied on participants' own ratings of familiarity for each stimulus using a questionnaire (see Procedure). The chords varied in their type and quality (see Table 1). We have provided all of our stimuli on our Open Science Framework (OSF) page (https://osf.io/5d8ws/?view_only=e8dd37e1ee1e438fb87769dcd1419b26). Due to the layout of notes in standard tuning, chords in less familiar positions required either a less familiar hand shape, or a shape not usually associated with the given chord type, despite producing the same auditory result as the familiar hand shape version of that chord.

While different fingerings might produce the same pitches, on real guitars, the timbre of the two versions of the chord might differ somewhat if different strings are used. The MIDI setup controlled for such timbral differences by using a MIDI piano sound. This

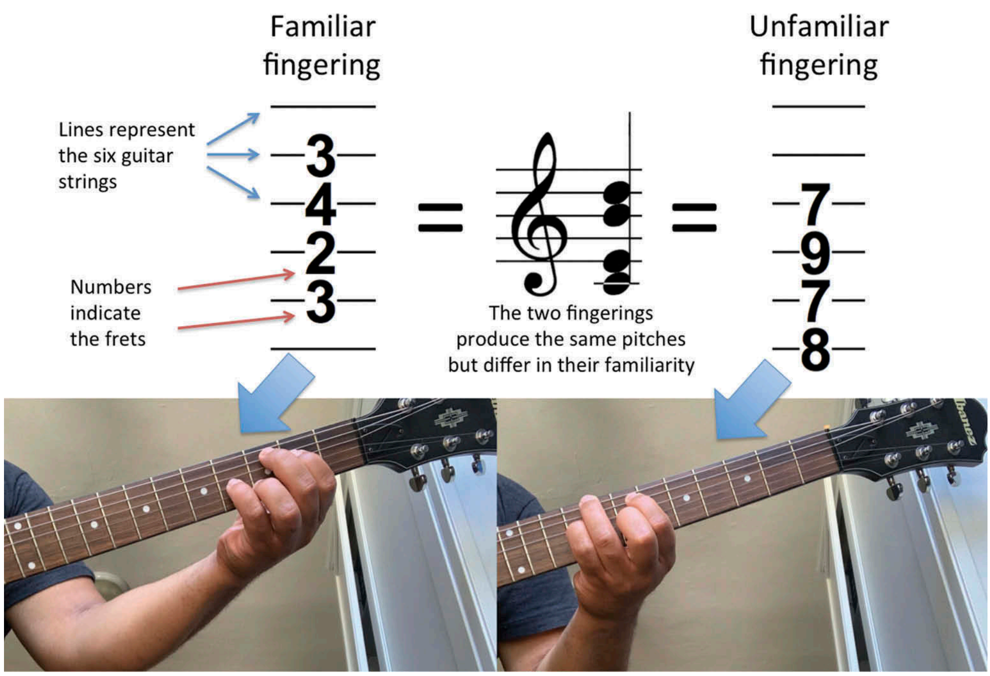

Figure 1. Familiar and unfamiliar fingerings. Each sounding chord could be produced by both a familiar and unfamiliar fingering. The two images show how different fingerings (one familiar, and one unfamiliar) can produce the same set of pitches.

Table 1. Chord types and incongruent version pairings.

Played Notes	Chord Type	Incongruent Heard Notes	Chord Type
48, 52, 59, 62	C Maj9	48, 52, 58, 62	C9
48, 52, 58, 62	C9	48, 52, 59, 62	C Maj9
50, 54, 60, 65	D7 #9	50, 55, 60, 65	Dmin11
50, 55, 60, 65	Dmin11	50, 54, 60, 65	D7 #9
55, 61, 65, 70	Gmin7b5	55, 61, 64, 70	Gdim7
55, 61, 64, 70	Gdim7	55, 61, 65, 70	Gmin7b5
53, 57, 63, 66	F7b9	53, 57, 63, 65	F7
53, 57, 63, 65	F7	53, 57, 63, 66	F7b9

Each of the eight chords had versions with familiar and unfamiliar fingerings. The numbers in the Played Notes and Incongruent Heard Notes are MIDI numbers encoding pitch, such that middle C on a piano corresponds to 60, with each integer representing one semitone (e.g., 61 is C-sharp). In the congruent condition for a given stimulus, the same pitches as the Played Notes were played back. If the feedback for a trial was incongruent, the Incongruent Heard Notes were instead played back. The played notes for each stimulus were represented in tablature to the participants in two different ways, as in the left and right panels of Figure 1. The full set of tablature images is included on our OSF page.

also controlled for the possibility that some participants might gain an advantage by being more familiar with a particular guitar sound, for example nylon-string acoustic versus electric guitar (though, note that we did not measure participant's familiarity with piano timbre beyond confirming that piano was not their main instrument). These controls are advantageous to our present experimental design, but we note that this limits our ability to investigate the role of timbral familiarity in perception-action coupling.

In the experiment, participants were prompted with single tablature diagrams with no text or labels. Tablature diagrams were created with the Encore music software program. These were visually presented on a Toshiba Satellite laptop via custom software created with MAXMSP (version 7.3.1), which also delivered auditory feedback (44.1kHz sampling rate, 16 bit depth) and recorded response data. Auditory feedback was either congruent or incongruent, and the familiarity of the guitar chord shape varied. This provided two factors for our analysis of the participants' behavioral performance from which our statistical models predicted reaction times and accuracy.

Procedure

Participants used Bose QuietComfort 25 noise canceling headphones, which canceled the sound from the actual guitar strings such that only the computer-generated sound could be heard. The experimenter confirmed with each participant that they could not hear the sound of the guitar string itself. Four participants reported that they could hear a slight amount of the sound, but that the MIDI-generated sound masked this faint sound such that it did not influence their performance on the task. Participants played chords on a Fender Esprit guitar fitted with a Fishman Tripleplay MIDI guitar pickup and responded via a Fishman FC-1 foot controller. Because MAXMSP takes some amount of time to render the MIDI sound, we conducted a latency test to ensure the jitter between the MIDI input and the sound rendering was low and confirmed the setup had an acceptable amount of jitter (3.55 ms).

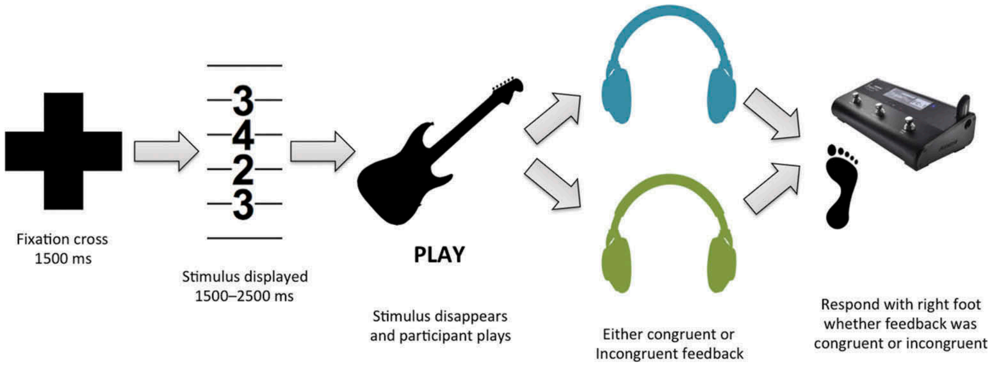

Figure 2. Schematic diagram of a single trial.

The participants sat wearing headphones in front of the laptop screen at a comfortable viewing distance. The schematic of a single trial is shown in Figure 2. The experimenter stood behind each participant at an angle to observe their responses and take notes without being directly visible. For each participant, we included 8 congruent and 8 incongruent trials for each of the 16 unique tablature diagrams (256 trials total). We divided these 256 trials into four blocks of 64 trials each, and randomized the order for each participant.

In each trial, participants were presented with a fixation cross lasting 1500ms followed by a tablature diagram, which was displayed for 1500–2500ms. This display time was variable in order to avoid establishing a groove between trials, and to keep participants attentive. Although participants could form their left hand shape on the guitar fingerboard as soon as they saw the tablature diagram, they were instructed not to strum the chord until the diagram disappeared and the software prevented the chord from sounding before this occurred. When the diagram disappeared from the laptop screen, participants played the corresponding chord on the same Fender Esprit guitar. Each chord shape had a congruent and incongruent feedback condition so that altered feedback was counterbalanced across familiarity. Thus in half of the trials the auditory feedback was altered by changing the pitch of one of the notes. Importantly, the alterations (Table 1) were always such that the resulting altered chord was itself present in the stimulus set to prevent participants from using an oddball strategy to solve the task. Participants then judged whether the feedback was altered or not, responding as quickly and accurately as possible by pressing either a left or right button (counterbalanced across participants) on the FC-1 foot controller. Feedback was given onscreen with the words “correct” or “incorrect” for responses, “too slow” if they did not respond within 4 seconds, “error” if they played the chord incorrectly (i.e., played a note not indicated by the tablature diagram) and “didn’t play” if they did not play the chord within 8 seconds. Reaction times and error rates were collected by the presentation software for analysis. The experiment lasted approximately one hour.

In a subsequent session, approximately two weeks later, all 21 participants ranked the familiarity of the stimuli by means of a questionnaire presented with MATLAB on the same laptop. The time in between sessions was an attempt to minimize the possibility that performance in the experiment influenced ranking of familiarity. Participants sat at a comfortable viewing distance from the screen with their guitar. Tablature diagrams were presented on the screen individually in random order with each diagram appearing a total of three times. The next diagram was prompted by a key press from the participant, who was instructed to try the chord shape on their guitar and rank its overall familiarity by pressing one of the keys 1–7, where 1 = "very unfamiliar, almost never use" and 7 = "very familiar, almost always use this." Each session lasted approximately 10 minutes. Because of possible ambiguity in the instructions that might have led participants to rate the familiarity of the chord position rather than the hand shape (since a particular hand shape might be used more often at certain positions along the fret board), an additional online survey was given to the same participants approximately 6 months later. The design was similar to the first ranking study except that the survey was given online using the Bristol Online Survey platform and the instructions emphasized that the familiarity rating referred specifically to the hand shape used to play the chord rather than any other attribute. Any potential bias introduced by some participants having more familiarity with the eight chord types is removed by the within-subjects measure of familiarity used in this study. Eighteen of the original 21 participants completed the second questionnaire.

Results

Data Analysis

To assess the effects of congruence and familiarity on behavioral performance, we constructed separate linear mixed effects models with the dependent variables reaction time and accuracy. For each dependent variable fixed effects factors of congruence (congruent vs. incongruent auditory feedback), familiarity rating, the congruence-familiarity interaction and occurrence were included, and one model was constructed for each familiarity rating. We reasoned that participants' responses may have gotten faster over the course of the experiment, so we controlled for this by including the additional fixed effect of "occurrence," which was the number of times a particular stimulus had occurred over the course of the experiment by that trial (e.g., the reaction time associated with the fourth time a particular stimulus was presented would have an occurrence value of 4, regardless of the congruence of the feedback – a maximum occurrence value is thus 16). We included the random effects of participant number – since participants differed overall in their reaction times – and chord number (1–8) regardless of familiarity – since the 8 different chord types may have introduced additional variance if some were easier to identify than others overall, regardless of which of the two fingerings was used to play them. Note that we constructed two models with this structure: one for each familiarity rating. Across participants, the overall familiarity rating had M = 4.30, SD = 2.09, and hand shape familiarity rating had M = 5.39, SD = 1.69. However, participants did not always use the full range of the Likert scales (the maximum range being 6). Across the participants, the overall familiarity rating ranges had M = 5.43, SD = 0.88, and the hand-shape familiarity rating ranges had M = 4.26, SD = 1.45. To account for this, we z-scored each participant's set of ratings (separately for each of the two familiarity metrics) and used those values in the linear models. This means that each of the two familiarity ratings are relative, not absolute.

The reaction time analysis only included data from trials with correct responses. Reaction times that were more than 2.5 standard deviations from the mean within participant were excluded from analysis. This resulted in excluding 2.67% of the data. The experimenter observed that one participant had significant trouble performing the experimental task (needing many reminders about which button on the foot controller corresponded to which response). Subsequent inspection of their data showed that their accuracy was 54.36%, which is below chance level according to a binomial test (p = .05) on included trials for this participant (trials in which they correctly played the chord), so they were excluded from the analysis. This participant was also one of the 3 who did not complete the second familiarity-rating questionnaire, and one of the 4 who reported hearing slight sound from the guitar.

We also conducted a mixed effects logistic regression with the same fixed and random effects, to predict whether the participant correctly responded to whether the auditory feedback was congruent (including trials in which participants were too slow to respond as incorrect). We did not allow for random slopes in our models. The models were constructed in R using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) and the statistical significance of our factors was assessed using the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017), which uses likelihood ratio tests with the full model compared to the model without each predictor variable of interest. The data tables and R script have been made available through our OSF page (the link is provided above in Stimuli).

Note that trials in which participants did not play the chord at all did not count as "incorrect" but were rather excluded from the analysis (on average across participants, this accounted for 1.97% ± 1.97% of the trials). Also, trials in which participants played the tablature diagram incorrectly were similarly excluded from the analysis (on average across participants, this accounted for 12.96% ± 7.54% of the trials). Our stimulus presentation software in MAXMSP automatically detected when chords were played incorrectly or not at all. Note that by contrast, if participants did indeed play the chord correctly in a given trial, but were too slow to respond or did not respond as to the congruence of the auditory feedback, this was counted in the analysis as an incorrect trial. It should also be noted that although participants may have interfaced with the equipment in slightly different ways – which could potentially introduce some variability in the response time data – the within-subjects experimental design prevents such variation from contributing to the effects described by our statistical analysis

Reaction Time Models

Figure 3 shows summary statistics for median reaction times by condition. For the linear mixed effects model with the overall chord familiarity rating, congruence had a significant effect, with incongruent stimuli raising reaction times by 81.87ms ± 33.61ms, $t(3264.00) = 2.44$, $p = .015$. Familiarity rating also had a significant effect with each additional standardized unit of familiarity lowering reaction times by 19.58 ± 4.91ms, $t(3269.00) = -3.99$, $p < .001$. Participants responded more quickly with congruent auditory feedback, and when the stimuli were familiar. Occurrence was also significant, with each occurrence lowering the response time by 11.41ms ± 1.60ms, t

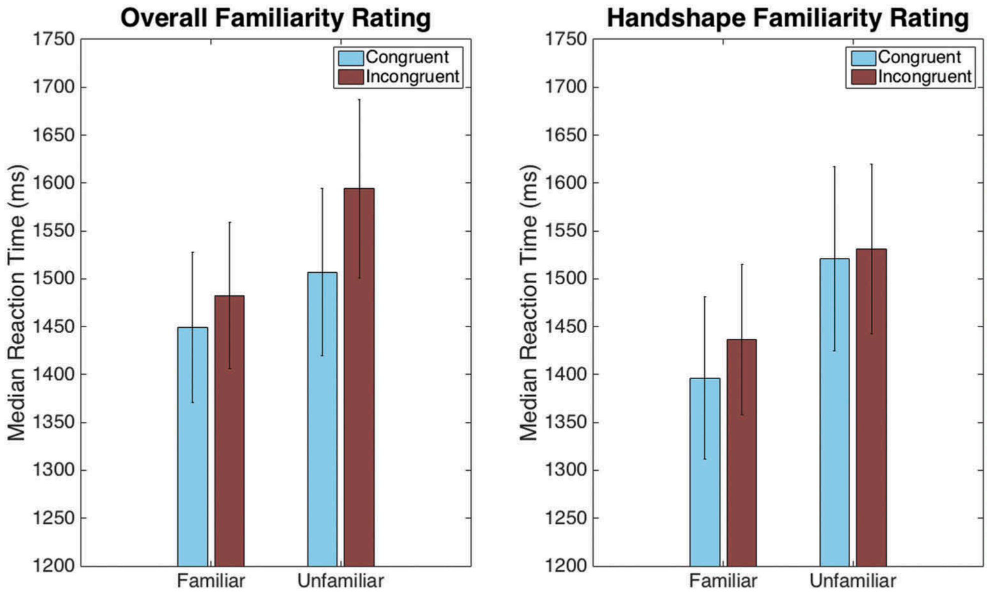

Figure 3. Summary statistics for reaction times. The bar heights represent the mean of the median reaction times for each participant in each condition. Error bars show one standard error above and below the mean. The categorical familiarity distinction visualized here was determined by using a median split of the familiarity ratings within each participant.

(3261.00) = −7.12, p < .001. The congruence-familiarity interaction was not significant (see Table 2, model 1).

For the model with the hand-shape familiarity rating, again, congruence had a significant effect, lowering reaction times by 62.77 ± 15.02ms, t(3067.80) = 4.18, p < .001. Each additional standardized unit of the hand-shape familiarity rating lowered reaction times by 66.26 ± 10.71ms, t(3068.10) = −6.19, p < .001. Occurrence still had a significant effect here with each occurrence lowering the response time by 13.88 ± 1.63ms, t(3063.00) = −8.53, p < .001. The congruence-familiarity interaction was also not significant in this model (see Table 2, model 2).

It should be noted that visual inspection of a plot of the residuals of these two models as a function of the fitted values suggested heteroscedasticity, with higher fitted reaction times having larger residuals than lower reaction times. We also assessed this with a Spearman correlation test (Yin & Carroll, 1990) that indicated that this relationship was significant (for the overall familiarity rating, r_s = .36, p < .001, and for the hand-shape familiarity model, r_s = .37, p < .001). Heteroscedastic models can potentially inflate Type I errors (Caudill, 1988). In order to account for this, we recomputed the mixed effects models with log-transformed reaction times, and also conducted 2 × 2 repeated measures ANOVAs by transforming the familiarity rating into a categorical variable (familiar vs. unfamiliar) using a median split of the ratings and ignoring occurrence (as visualized in Figure 3). The models with the log-transformed reaction times reduced this heteroscedasticity (for the model with the overall familiarity rating, rho = .15, p < .001, and for

Table 2. Summary statistics for the linear mixed effects models for reaction times.

	Estimate	Std. Error	df	t value	Pr(>|t|)	Sig.
Model 1						
(Intercept)	1722.50	86.75	27	19.86	< 2e-16	***
Congruence	81.87	33.61	3264	2.44	0.0149	*
Familiarity (overall)	−19.58	4.91	3269	−3.99	6.81E-05	***
Occurrence	−11.41	1.601	3261	−7.12	1.28E-12	***
Congruence:Familiarity	−5.57	7.01	3261	−0.79	0.427	
Model 2						
(Intercept)	1622.63	85.23	22.50	19.04	2.22E-15	***
Congruence	62.77	15.02	3067.80	4.18	3.01E-05	***
Familiarity (hand shape)	−66.26	10.71	3068.10	−6.19	7.02E-10	***
Occurrence	−13.88	1.627	3063	−8.53	< 2e-16	***
Congruence:Familiarity	5.68	15.76	3063.20	0.36	0.719	

Note. Model 1 used the overall familiarity rating, and model 2 used the hand shape familiarity ratings. Reaction time estimates and standard errors are in ms.
a*p* < .05. ***p* < .01. ****p* < .001

model with the hand-shape familiarity rating, rho = .17, $p < .001$), while preserving the statistical significance of the same fixed effects.

The repeated measures ANOVAs used the median reaction time for each participant in each condition. For full details of these models, please see the Supplementary Materials. The model with the original overall familiarity rating returned a significant effect of congruence ($p = .009$) and familiarity ($p = .027$), and a marginally significant interaction ($p = .068$). The model with the hand-shape familiarity rating returned a significant effect of familiarity ($p = .004$), but not congruence ($p = .179$), and no interaction ($p = .844$). We also conducted similar ANOVAs on the accuracies for each condition (again, one for the overall familiarity rating and one for the handshape familiarity rating). Both models returned significant effects of congruence (both $p < .001$) and familiarity ($p = .011$ and $p = .006$, respectively), and no interactions ($p = .290$ and $p = .122$, respectively). These additional models were thus consistent with our main findings and increase our confidence that the effects in our original model are not in fact Type I errors; however, the lack of effect of congruence in the reaction time model with the hand-shape familiarity rating warrants further discussion (see Discussion).

Accuracy Models

Figure 4 shows summary statistics for accuracy values by condition. The mixed effects logistic regression used to predict whether participants answered correctly or not returned similar results. For the model with the general familiarity rating, congruence significantly increased the log-odds of a correct response, $B = 0.87$, z = 10.81, $p < .001$, as did the familiarity rating, $B = 0.16$, z = 2.53, $p = .011$, and the occurrence, $B = 0.03$, $z = 2.93$, $p = .003$. There was no interaction between familiarity and congruence. The model with the hand-shape familiarity rating returned similar results. Congruence was a significant predictor of a correct response, $B = 1.07$, $z = 11.46$, $p < .001$, as was the hand-shape familiarity rating, $B = 0.24$, $z = 3.31$, $p = .001$, and occurrence, $B = 0.05$, $z = 4.54$,

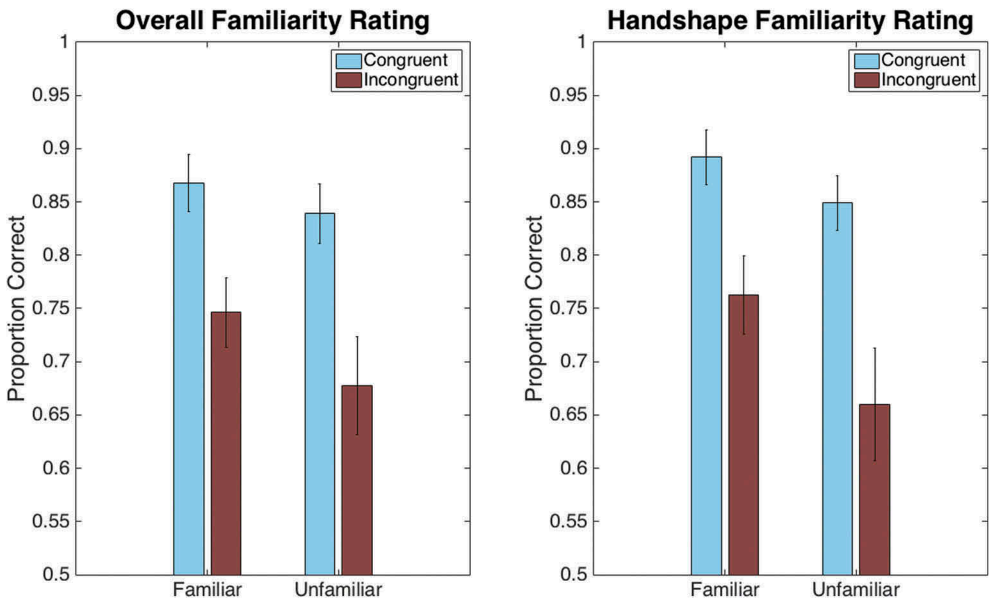

Figure 4. Summary statistics for accuracy values. Error bars show one standard error above and below the mean. The categorical familiarity was determined by using a median split of the familiarity ratings within each participant.

$p < .001$. In both models, congruence, familiarity, and later-occurring stimuli predicted a higher log-odds of a correct response. We also provide repeated measures ANOVA analyses in order to be compared with the analogous reaction time ANOVA models we provide. Those analyses also returned significant main effects of congruence and familiarity, but no significant interactions. See the Supplementary Materials for full details of those models.

Discussion

We conducted an experiment investigating the relationship between the familiarity of particular chords and the acuity of the auditory images they induce as measured by participants' sensitivity to altered feedback, with the hypothesis that more familiar movements would facilitate better performance because of more accurate forward models. When participants played more familiar chords and used more familiar hand shapes, they were faster and more accurate in their judgements of the congruence of the auditory feedback, hence our main finding supports this hypothesis. We tested both for the familiarity of each *chord shape* (particular hand positions at particular places on the fretboard) and also the *hand shape* (the configuration of the hand regardless of its position on the fretboard) used to play each chord, in separate questionnaires with the participants of the main study. There were significant effects of both measures of familiarity: more familiar hand shapes had faster responses and higher accuracy in judging the congruence of the auditory feedback.

These results suggest that despite years of exposure to repeated associations between individual locations on the fingerboard and their corresponding musical pitches, guitarists do not simply use this place-to-pitch mapping of individual notes and combine these to form expectations of how a chord will sound. Rather, there is a heterogeneity of the gesture-to-sound mapping such that some hand shapes (regardless of their particular fret position on the fingerboard) have a stronger and more accurate coupling to the intended sound than others. This might seem at odds with some findings suggesting that in musical experts there is a flexibility in the way musical goals are realized motorically (Novembre & Keller, 2011; Palmer & Meyer, 2000). However, these studies investigated motor independence in the realization of musical goals in pianists, and because of the one-to-one key-to-pitch mapping of the piano, the way that familiarity of motor representation was manipulated introduced unusual hand shapes for the chords. In contrast our stimuli exploit the many-to-one mapping of the guitar fingerboard to allow the same hand shape to play a familiarly associated chord or a less familiar one in an ecologically valid manner. The finding that responses were slower in the unfamiliar condition in the present study raises interesting questions about individual and group differences in the flexibility of motor representations for implementing musical goals. In particular, it opens questions about the topography of perception-action coupling in other spaces besides fretboard-space: given that there is variety with respect to certain hand movements, one can ask what factors (besides mere familiarity) lead to the variation in coupling strength, such as similarity between movements in terms of their motor representations, and between musical structures in music-theoretical terms (like harmonic function). This line of reasoning about future research further shows how our present work builds on past work that has also investigated abstract features of perception action coupling. Musical gestures are more abstract than mere fret-to-pitch mapping, and hand shape familiarity is one way to demonstrate the role of gestures in perception-action coupling, as we have done.

In contrast to the ANOVA model that used the overall familiarity rating, the ANOVA model with the hand-shape familiarity rating did not return a significant effect of congruence, though congruent stimuli in this model still tended toward having lower reaction times (for congruent stimuli, $M = 1459.43$ ms, $SD = 347.84$ ms; for incongruent stimuli, $M = 1492.76$ ms, $SD = 347.84$ ms). This could be due to the reduced sample size used for that model (since 3 participants did not complete the later questionnaire). Another potential problem is that 5 participants reported gaining familiarity with the chords during the intervening months before the second questionnaire. This could have resulted in some chords being coded as "familiar" when in fact they were "unfamiliar" at the time of the experiment. However, this would only serve to weaken the effects of familiarity: if unfamiliar chords do have slower and less accurate responses, mixing those miscoded trials with the truly "familiar" chords would only decrease the difference between the conditions. Yet, we still observed an effect of familiarity in this model.

The lack of interaction between the familiarity and congruence factors was surprising. One might expect that familiar hand shapes facilitate more accurate forward models such that the effects of congruence should be stronger. If the forward model is less accurate or distinct in the unfamiliar condition, then the mismatch between the anticipated and heard sound would be less acute, and while overall performance might be worse than in the familiar condition, one would expect less difference between performance for congruent and incongruent stimuli. For example, in an extreme case, a movement might be so unfamiliar that the forward model is completely absent such that incongruence should not have any impact. Yet, in our study, the unfamiliar chords did not significantly differ from the familiar ones in how much congruence affected them. It could be that despite some stimuli being relatively unfamiliar, some of those trials could have had strong enough forward models so as to have similar reaction times as the familiar stimuli. This could be the case considering our reaction time analysis only considered correct trials. However, the logistic model for accuracy did not show an interaction either. Another explanation pertains to the abstraction of musical gestures. Since incongruent feedback slows reaction times by conflicting with the expected sound, and since less familiar movements were still affected in this way, it could be that there is indeed some generalization of the technique of the instrument.

Finally, considering that participants were slower for the unfamiliar stimuli, it could be that performers used a different, slower process to identify congruence. In line with our theoretical framework, a good way to disambiguate these possibilities would be to run an ERP study using a similar procedure to our present study. Cases in which auditory feedback does not match the intended movement, i.e., performance errors or artificially altered feedback, have been shown to induce error-related and feedback-related negativities (Lutz, Puorger, Cheetham, & Jancke, 2013). If incongruent feedback for unfamiliar movements still produces these ERP component effects for experienced instrumentalists, this would be strong evidence for the abstraction of forward models across the instrument.

We observed a training effect over the course of the task. Participants got faster and more accurate on repeated presentations of the stimuli suggesting that the unfamiliar auditory-motor couplings could be learned relatively quickly (Bangert & Altenmüller, 2003). However, our study was not designed to reliably quantify the magnitude of this effect over the course of the experiment. Further research could specifically investigate this question, and elucidate the respective roles of familiarity and congruence to investigate the time-course by which acquired expertise modulates these effects.

Given that we collected response times only after the participants had already moved their left hand to form the chord shape, it is not clear whether it was the right hand movement per se or the combination of right hand movement with left hand proprioceptive and haptic sensation that was responsible for these results. Given that the right hand movements did not differ in familiarity between conditions the latter interpretation seems more likely. Regardless, our findings still show how familiarity of particular movements with their associated proprioceptive and haptic sensations influence the speed and accuracy of responses, though these features could potentially be dissociated in future studies.

In the broader context of perception-action coupling, the study of musical expertise offers an excellent opportunity to investigate the cognitive processes involved in the context of training-induced differences. Our extension of the AAF paradigm to the guitar, which differs from the piano both motorically and in its pitch-to-place mapping, sheds further light on the role of instrumental affordances. Our results are compatible with the theoretical framework of grounded cognition (Barsalou, 2008), according to which cognition, movement and the person-instrument interface are all enmeshed at a level more abstract than a simple place-to-pitch mapping. Following this, future studies could investigate whether artificial alterations of chords to ones that are functionally related to the played chord are more difficult than functionally unrelated chords. Also, further research with the guitar could extend this result for chords to involve melodic phrases implemented in different fingerboard configurations; melodies can be considered in terms of motor-sequence learning (Krakauer, Hadjiosif, Xu, Wong, & Haith, 2019), and varying the individual movements used to play the same melody – as is possible on the guitar with its many-to-one mappings – could thus test gestural abstraction of motor sequences. Similarly, future research could be extended and generalized to other melodic instruments, for example aerophone instruments such as brass or woodwind which are not only present a motorically different interface to the piano and guitar, but also do not have the same instrumental implementation of pitch-to-place mapping.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability

Data and analysis scripts for this project have been made available on the Open Science Framework and can be accessed here: https://osf.io/5d8ws/?view_only=e8dd37e1ee1e438fb87769dcd1419b26

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