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Society for Education,

Psychology of Music
2016, Vol. 44(4) 847–863

nonmelody voices, and that the error pattern varied according to the performer's interpretative goal. In addition, errors were found to be less frequent in the highest voice regardless of the interpretative goal. Again, this relationship is mirrored in perception studies reporting that lis-teners are generally more sensitive to changes in the highest voice (Dewitt & Samuel, 1990; Palmer & Holleran, 1994), an effect that has been documented at a pre-attentive level in elec-trophysiological studies (Fujioka, Trainor, Ross, Kakigi, & Pantev, 2005). The current study extends beyond Palmer & Van de Sande (1993), who examined three-voice textures with one hand controlling one voice and the alternate hand controlling two voices, by investigating the effect of melodic emphasis using a four-part piece with two voices in each hand, thus keeping the assignment of voices to hand fixed across conditions.

One aspect that has been unexplored so far is whether error rates are lower for musically salient elements such as recurring musical motives or themes. Given the effects of musical structure and melodic emphasis on error rates (Palmer & Van de Sande, 1993), performers could be expected to make fewer errors when playing motivic passages than non-motivic pas-sages; likewise, listeners would be expected to be more sensitive to errors in motivic passages. Here, we tested the effect of musical salience (motivic vs. non-motivic notes) by analyzing per-formances of an organ fugue in which recurring motives are clearly delineated.

Finally, we sought to determine whether individuals keeping

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Table 1. Error frequencies and percentages.

Piece	Score notes (played notes)	Score-based errors					Non-score-based errors		
		Deletion errors		Pitch errors	Timing errors	Total score errors	Insertion errors		Total non-score errors
		Omissions	Added ties*				Intrusions	Repetitions	
Premier Agnus	15,360 (15,231)	35	98	37	38	208	56	16	

In all cases, error rates were modeled using a logistic regression model, in which the dependent variable represented the probability of error per score note (in other words, the probability that a given note is wrongly played by the performer), rather than a continuous error proportion or rate across the entire melodic sequence. Because onset density was shown to influence error rate, it was included as a covariate in order to take its effect into account.[6]

Melodic emph32ropor

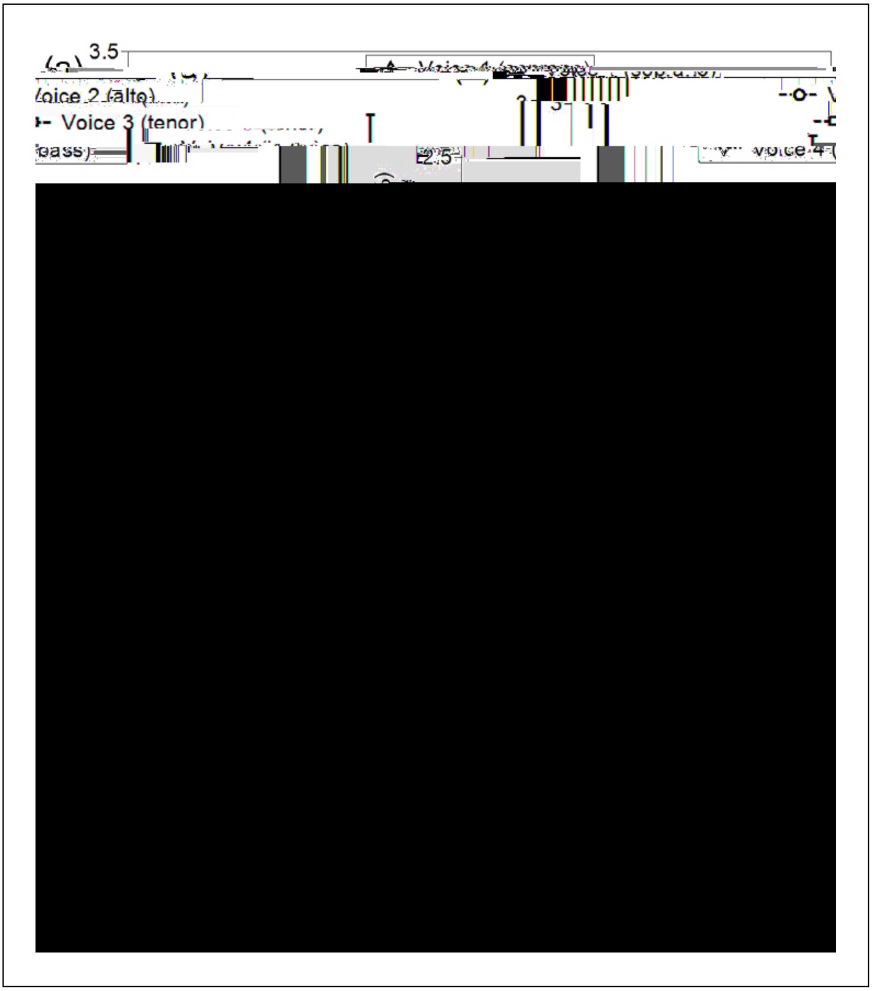
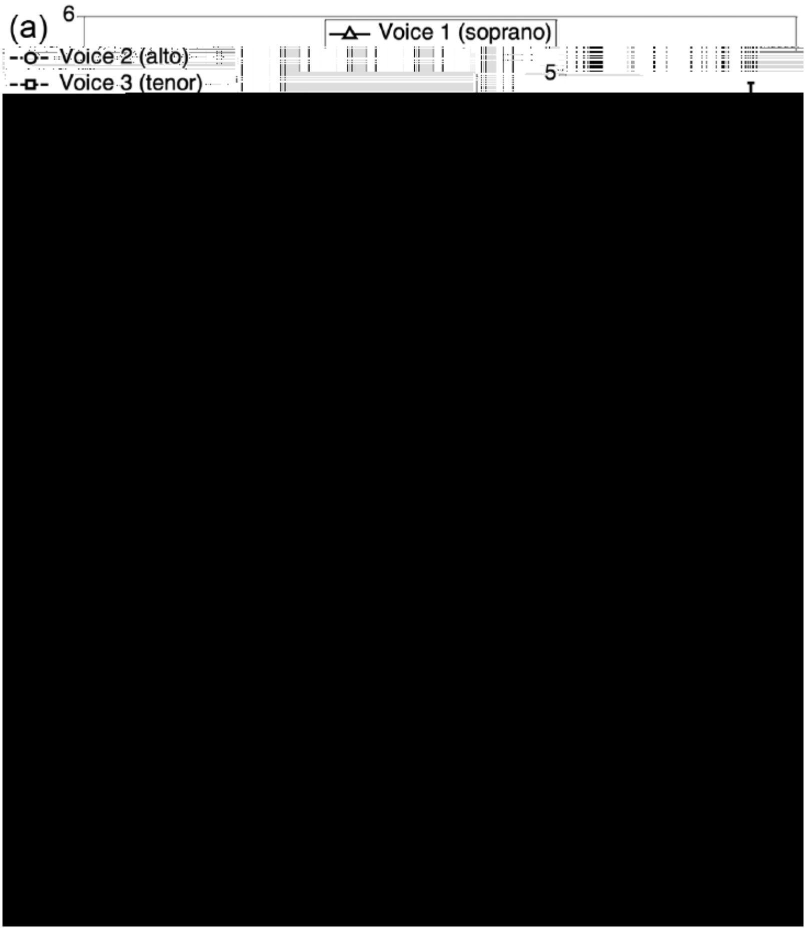


Figure 1. Effect of melodic emphasis on error rate for the Premier Agnus. Mean error rates (in %) averaged across performers. Error bars represent standard errors of the mean. (a) Error rates by voice. (b) Error rates by hand and voice position.

from the first countersubject, which saturate the fugue (see Supplementary Materials; brackets indicate motivic material). All other sections of the piece were considered non-motivic for the purpose of this analysis.

As expected, error rates were lower for the highest voice (soprano) and for outer voices (Figure 3). Error rates were also significantly lower for motivic notes than for non-motivic ones. Finally, error rates were higher for the left hand than for the right hand or the pedal. Given that the majority of motives occur in outer voices in the Dorian fugue, presumably because the composer sought to ensure their perceptual salience (Huron, 1989; Huron & Fantini, 1989) and that all pedal notes belong to an outer voice in this piece,[7] the effects of voice position (and, by extension, those related to specific voices), musical salience, and limb assignment are interdependent to a certain extent. Thus, a rigorous statistical treatment of these effects should consider the combined effects of voice position and musical salience, while excluding the pedal part



from analyses considering interactions between voice position and limb assignment (note that multicollinearity cannot be assessed between categorical factors such as voice assignment, limb assignment, or voice position). A repeated-measures logistic regression on error rate by voice position (inner/outer) and musical salience (motivic/non-motivic notes), excluding the pedal part showed significant effects of voice position, $F^2(1) = 75.3$, $p < .001$, and musical salience $F^2(1) = 11.7$, $p < .001$.

An analysis combining the effects of voice position, musical salience, and hand assignment (left/right, excluding pedal notes) in a single model yielded a more complex picture, with main effects of voice position and musical salience (but no effect of hand assignment) and significant interactions between hand assignment and position, as well as hand assignment and musical salience (Table 2). Whereas error rates for motivic notes in outer voices were comparable for both hands, they were markedly higher in the left hand for non-motivic notes belonging to inner voices (Figure 4).

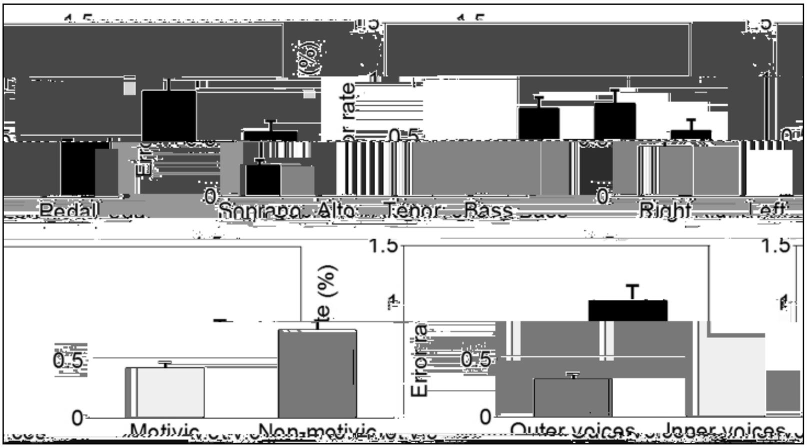


Figure 3. Error rates for different structural note categories for the Dorian fugue. Mean error rate (in %) for all categories, averaged across performers. Error bars represent standard errors of the mean.

Table 2. Repeated-measures logistic regression on error rates for the Dorian fugue (with onset density as covariate).

Source	d.f.	F^2	p
Voice position	1	110.9	< .001
Motivicity	1	8.58	.003
Hand	1	1.27	.260
Voice position × Musical salience	1	0.44	.507
Voice position × Hand	1	6.33	.012
Musical salience × Hand	1	14.4	< .001
Voice position × Musical salience × Hand	1	3.49	.062

Effects of musical texture: Homophonic versus polyphonic piece

Palmer and Van de Sande (1993) had previously shown that the proportion of harmonically related errors was higher for homophonic pieces than for polyphonic pieces. Here, we analyzed the effect of musical texture on two error types, namely pitch substitutions (replacing a score note by a note with the wrong pitch) and intrusions (playing additional notes not indicated in the score), by evaluating the type of errors produced in performances of a mostly homophonic piece (Wachet auf) and of a polyphonic piece (Premier Agnus). These two pieces are of similar length, with a mostly four-voice texture throughout (the average number of active voices per score event, or voice density was 3.98 for both pieces), thus providing an adequate basis for comparison.

Pitch and intrusion errors were categorized into three types: errors related only to the har monic context, errors related only to the melodic context, and errors that were both harmonically and melodically related. An error was defined as harmonically related if its pitch was equivalent, via octave transposition, to that of another score note present in the same score event. An error was defined as melodically related if another note with the exact same pitch was found in the score events immediately preceding or following the onset of the wrong note. Following Palmer & Van de Sande (1993), chance estimates were computed for harmonic relatedness, corresponding to the average number of pitch classes per score event divided by the total number of possible pitch classes (12); equal probability was assumed for all pitch classes. Statistical analyses were conducted both on the aggregate data (chi-square test) and on individual performers (two-tailed Wilcoxon paired-sample exact tests) to test for differences between proportions and chance estimates.

Table 3 shows that the proportion of melodically related errors was greater in the polyphonic piece (Premier Agnus) than in the homophonic piece (Wachet auf), whereas the proportion [illegible] an

Consistency and individuality of error patterns

To evaluate the consistency and individuality of performers' error patterns, all pairs of performances were compared by tabulating the frequency of co-occurrence of errors in the same score event in different performances. Because this comparison was conducted on an event-by-

Table 4. Mean Jaccard coefficients for error patterns between all pairs of performances for all three pieces.

This discrepancy between our findings and those of earlier studies regarding hand and voice assignment effects could be explained by differences in the musical stimuli (number of voices controlled by each hand), the skill level of the performers, or the experimental instructions: this study used natural performance tempi, whereas Palmer & Van de Sande (1993) elicited errors by asking performers to use faster tempi. The differential effects of voice position and musical salience by hand assignment observed for the Dorian fugue suggest that the right-hand advantage can probably best be explained by a combination of hand-dominance effects and attentional processes. In a series of articles, Peters (1981, 1985) reported that right-handers typically performed bimanual tasks better when the right hand took the “figure” and the left hand took the “ground” of a dual movement, and that subjects’ performance could be influenced by directing their attentional processes. If we assume that performers directed more attentional resources towards perceptually or musically salient notes, this model would fit nicely with our observations on the Dorian fugue. Indeed, there was no clear right-hand advantage in terms of error rates for salient notes, whereas the left hand was at a clear disadvantage for less salient notes. However, a thorough study of the effects of hand assignment and handedness on error rate would entail a comparison of the performances of left-handed and right-handed keyboardists of equivalent skill level and degree of familiarity with the musical pieces; this project was beyond the scope of the present study.

As mentioned above, organists made fewer errors in the outer voices, and they made more harmonically related errors in a homophonic texture than in a polyphonic one. These findings, which replicate previous results (Palmer & Van de Sande, 1993), are consistent with measures of listeners’ sensitivity to altered pitches in performance, which is higher for errors in the outer voices and especially in the highest voice, and for harmonically unrelated pitch errors than for related ones (Palmer & Holleran, 1994). Moreover, our finding that error rates were lower for motivic notes than for non-motivic ones is in line with Dewitt and Samuel’s (1990) observation that listeners are more proficient at detecting changes in familiar than in unfamiliar melodies. These complementary observations regarding the production and detection of performance errors suggest that performers’ and listeners’ mental representations of the score are well matched in terms of the relative perceptual and musical salience of structural note categories. These relationships may be encapsulated by the following statement: the likelihood of a note, or group of notes, being wrongly played is inversely correlated with its degree of perceptual and musical salience.

Our experimental manipulation of melodic emphasis showed that organists made fewer errors in a given voice when it was emphasized than when it was not. This indicates that their mental representations of a musical score are flexible, and suggests that interpretations of the same piece that highlight different musical features lead to distinct conceptualizations of the

Ethical approval

This work was approved by the Research Ethics Board of McGill University, Montreal, Canada (REB Certificate 67-1104).

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by a doctoral fellowship from the Social Sciences and Humanities Research Council of Canada (SSHRC 752-2003-2178) and a student award from the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) to Bruno Gingras, as well as grants from the Natural Sciences and Engineering Research Council (RGPIN 298173-2010; RGPIN 312774-2010) and Canada Research Chairs awarded to Caroline Palmer and to Stephen McAdams.

Notes

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