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Technical Report UU-CS-2008-026
September 2008

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ISSN: 0924-3275

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ON MEASURING MUSICAL STYLE – THE CASE OF SOME DISPUTED ORGAN FUGUES IN THE J. S. BACH (BWV) CATALOGUE[1]

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Abstract. *. In this paper a computational approach to musical authorship problems is described in which machine-learning algorithms are used to recognize personal musical styles. The algorithms learn characteristics from representative examples and are able to use the obtained "knowledge" to classify previously unseen compositions.*
The data consist of several organ fugues that are now in the catalog of J.S. Bach (BWV 534/2, 536/2, 537/2, 555/2, 557/2-560/2 and 565/2). With a nearest neighbor classifier, these disputed fugues have been compared to a number of fugues indisputably by J. S. Bach as well as the contenders J. L. Krebs, J. P. Kellner and W. F. Bach. This comparison has been done in a subspace that is spanned by a selected optimal sets of features. It appears that this comparison provides valuable contributions to the discussions about the authorship of these pieces.

1 BASES FOR COMPOSER ATTRIBUTIONS

One task of musicology is to study the musical past A common approach has been to provide an overview of the most important composers of each era together with their compositions, then to study the relationships of these compositions to each other and to the musical and non-musical historical contexts. A complementary activity has been the preparation of critical editions of scores. In these activities the question of authorship remains paramount. If we want to present the most important composers and their works, we need to know who composed what. If we want to make a critical edition of the works of a certain composer, we cannot escape making decisions about disputed compositions. Problems may be caused by conflicting attributions among plural sources, the lack of an authoritative source contemporary with the composer, an incomplete source, or an anonymous source which tradition holds to be by the composer. Attributions of the same work to multiple composers is a common phenomenon of European works of the fifteenth through nineteenth centuries.

Both external and internal evidence may be used to solve authorship problems (Love 2002). In many cases, however, external evidence of a decisive nature is lacking. Here, internal evidence becomes more important. For music, stylistic evidence seems the most important

[1] This is a modified version of P. van Kranenburg (2008). "Assessing Disputed Attributions for Organ Fugues in the J.S. Bach (BWV) Catalogue". *Computing in Musicology* 15, p. 120-137.

kind of internal evidence. In order to assess stylistic evidence one must have a model that is able to represent musical styles in such a way that specific instances of it can be associated with a composer's personal style to a unique degree. In manual practice, proof by example is often used to support an attribution on stylistic grounds. The most pertinent feature may be a distinctive motif or chord progression that is present both in the disputed work and in an undisputed composition. Such similarities might, however, be occasional. If we want to support an attribution in a statistically sound way, we have to use events which occur frequently (such as notes and intervals).

Computer-based assessment of musical authorship was first extensively explored by Trowbridge (1982; 1985-6), who revealed differences in style among four Renaissance composers (Gilles Binchois, Antoine Busnois, Guillaume Dufay, and Johannes Ockeghem) by comparing the average values of 16 quantifiable features (Trowbridge 1985-6). The repertory evaluated consisted of 92 Renaissance chansons, of which twothirds exist in a single manuscript copy with scribal attribution. Many of the rest are anonymous in at least one source, a few in more than one source. Many of the features are coincidentally similar to those used here. They included melodic intervals, harmonic intervals, chord types, bass progressions, root progressions, root distributions, prepared dissonances, chord durations, chord motion, texture reduction, melodic direction, rhythmic activity, average melodic range, relative melodic motion, voice crossing, and harmonic range. A good account of still earlier systems for quantitative analysis is given in Trowbridge (1982). For polyphonic music Trowbridge's thesis is by far the most thorough and comprehensive of its time. Far more prevalent today are studies that isolate and analyze musical features for differentiation of pieces by genre (e.g., McKay and Fujinaga 2004), mood (e.g., Dannenberg 1997), or idiosyncratic traits of individual composers (e.g., Cope 1991, Cope 1998).

2 A MACHINE LEARNING APPROACH TO STYLISTIC ASSESSMENT

Our approach to authorship problems employs machine learning algorithms (see Duin & Tax 2005). These algorithms learn characteristics of musical styles from representative examples, and are then able to use the obtained knowledge to classify previously unseen compositions. In an earlier publication the authorship of the fugue for organ in F minor (BWV 534/2) was evaluated (Backer and Van Kranenburg 2005). In the current article, another classification algorithm is used and the dataset extended with eight additional disputed fugues listed in the Schmieder (BWV) catalogue (1950/2nd rev. edn. 1990), and with six control compositions by Johann Peter Kellner.

3 MODELING MUSICAL STYLE

In Style and Music Leonard Meyer (1996) developed a theory of musical style that can be used as a starting point for studies that compare musical styles algorithmically. He defines style as *a replication of patterning, whether in human behavior or in the artifacts produced by human behavior, that results from a series of choices made within some set of constraints* (Meyer 1996: 3). In the process of composing, a composer is subjected to certain constraints while making his choices. Meyer distinguishes three levels of constraints. *Laws* (1) are universal. One cannot, for example, ask a piccolo to play a contra G. *Rules* (2) are intracultural. It is in the rules that music from the Renaissance differs from music from the Baroque. *Strategies* (3) are constraints to which the composer subjects himself within the rules of a certain culturally established style. Thus it is in the strategies that the music of G. F. Handel differs from the music of G. Ph. Telemann.

Not all strategies reside on a conscious level. Certain patterns are ingrained during the training and development of a composer and are not replicated consciously every time during the process of composing.

Meyer indicates the necessity of statistics: *since all classification and all generalization about stylistic traits are based on some estimate of relative frequency, statistics are inescapable* (Meyer 1996: 64). It can be expected that each composer has idiomatic, countable patterns that are more often replicated in his works than in compositions by other composers. The task is to find features in which such patterns are reflected.

4 THE DATASET

4.1 Selected Features

There is no well tested theory available that predicts which features have to be used to solve a particular authorship problem. Therefore, we do an “educated guess” at features that may have discriminative power. The subset of features that can be used to solve the authorship problem in question will be selected algorithmically.

Small scale features are preferable, because the algorithms to extract them are less complicated and the results less ambiguous. It is, for example, not obvious how to quantify the extent to which a composition resembles a certain sonata form, but it is less difficult to count the number of thirds. Because in the current study we are dealing with polyphonic music (fugues), the relations between the voices are important. The composer must know, for example, whether a dissonant interval can be written between two voices, how long that interval is allowed to sound, and what can follow. It can be expected that a composer develops certain strategies to handle these situations. This can result in replicated patterns in the distances between the voices.

The following 20 features are chosen:

Features 1–9: Vertical intervals weighed by duration. The total duration of all occurrences of each specific vertical interval is computed and at the end divided by the total duration of all intervals in all voice pairs. The intervals are folded onto one octave (e.g., a tenth is counted as a third). If the same pitch occurs in more than one voice, it is taken into account only once.

1. Seconds between parts
2. Thirds between parts
3. Perfect fourths between parts
4. Augmented fourths between parts
5. Diminished fifths between parts
6. Perfect fifths between parts
7. Sixths between parts
8. Sevenths between parts
9. Octaves between parts

Features 10–12: Parallel motion. The quantity of parallel thirds, fourths, and sixths is computed in the same way as for Features 1–9 . The total duration of all intervals involved in these parallels is computed and divided by the total duration of all intervals in all voice pairs.

10. Parallel thirds between parts
11. Parallel fourths between parts
12. Parallel sixths between parts

Features 13–15: Dissonance treatment. Perfect primes, minor and major thirds, perfect fourths, perfect fifths, and minor and major sixths are considered consonant. A fourth is considered dissonant if it is between the lowest voice and one of the upper voices. All other intervals are considered dissonant.

13. Suspension resolved stepwise in lower voice. The total duration of all intervals involved in such suspensions is computed and divided by the total duration of all intervals in all voice pairs.
14. Dissonance. The fraction of the score in which the sonorities are dissonant.
15. Bars beginning with dissonance. The percentage of bars that begin with a dissonant sonority.

Feature 16. Voice density. The average number of voices active in the composition. This is normalized for the total number of voices. Only bars that are strictly polyphonic (i.e., those in which more than one voice is active and in which each voice has not more than one note at the same time) are taken into account.

Features 17–19: Entropy measures. Computed according to the concepts harmony and sonority as defined by Robert Mason (1985) and Shannon's entropy formula (1948). In the definition of Mason, a sonority is a certain type of chord, regardless of inversion, pitch, or doubling of tones. Each sonority has a unique number. The only difference between harmony and sonority is that in the case of harmony the pitch is taken into account. E.g., the F-major and G-major triads are the same sonority, but different harmonies.

17. Harmony entropy. For each harmony the probability of occurrence is estimated by computing the total duration of all occurrences of the harmony and dividing that by the total duration of the piece. From these estimated probabilities, the entropy is computed.
18. Pitch entropy. Of each pitch the frequency of occurrence is estimated by computing the total duration of all occurrences and dividing that by the total duration of all pitches. From these estimated probabilities, the entropy is computed.
19. Sonority entropy. This feature is computed in the same way as Harmony entropy.

Feature 20. Time slice stability. The consistency of the length of successive time slices (e.g., the time interval between two changes in the music). Stability is computed by dividing the standard deviation of the lengths of the time slices by their mean length. This normalization is necessary in order to compare pieces with different time signatures. A low value means that the music is more like a steady stream, while a larger value indicates more diversity in rhythm. Bars which are not strictly polyphonic (see Feature 16) are ignored in computation.

4.2 The Compositions

Four composers are represented in the control dataset: J. S. Bach (1685–1750), his son Wilhelm Friedemann Bach (1710–84), his student Johann Ludwig Krebs (1713–80), and Johann Peter Kellner (1705–1772), who was a great admirer of J. S. Bach and played an important role in the copying and transition of Bach's organ compositions. Not many other composers among the students and contemporaries of J. S. Bach might have composed fugues comparable to those of J. S. Bach. However, an assignment of a disputed fugue to one of these four composers does not lead automatically to an attribution. The possibility that a composer not represented in the dataset wrote the piece should be kept open. In general, it is desirable to have external evidence that points exclusively at only a few candidates before pursuing the stylistic approach in the hope of making a definitive attribution.

Because of the time consuming process of data entry, not all fugues by J. S. Bach and J. L. Krebs were encoded. To lower the probability of incorporating misattributions somewhat, only the fugues of Kellner that appeared in print are incorporated. In the case of W. F. Bach, the included five fugues are the only ones suitable for our purpose. In all, 35 works of undisputed authorship were encoded. See Table 1.

5 DATA-ANALYSIS METHODS

To increase the amount of data available for control purposes, each composition was cut into overlapping segments of 30 bars, such that Segment 1 contains bars 1-30, Segment 2 contains bars 2-31, etc. (see Figure 1 for a generalized view). To produce reliable values, the minimum length of a segment has to be around 30 bars (Backer and Van Kranenburg 2005).[2] Since there is a large degree of redundancy from one segment to the next, however, the window measurements are not independent. This must be accounted for when applying machine learning algorithms. Bars that are not strictly polyphonic are ignored in the process of splitting.

Composer	**Compositions**
J.S. Bach	BWV 535a/2, 535/2, 538/2, 540/2, 541/2, 542/2, 543/2, 545/2, 547/2.
Krebs	Fugue in C minor (I, 2), E major (I, 5), F minor (I, 6), G major (I, 8), F major (II, 13), F minor (II, 14), F minor (II, 15), B flat major (II, 19).
W.F. Bach	Fk 33, 36, 37, Add. 211/1, Add. 211/2.
J.P. Kellner	O08:01, O08:06, O08:07, O08:[C], O08:[F], O10:02.
Disputed fugues	BWV 534/2, 536/2, 537/2, 555/2, 557/2-560/2, 565/2.

Table 1. *The incorporated organ fugues. The J. S. Bach numbering follows Schmieder (1990); that for Krebs, the edition of organ music by Weinberger (1985); for W. F. Bach, the catalog of Falck (1956), with additions by Peter Wollny (1993); for Kellner, the catalog by Claus (1999). Two fugues by Kellner not yet listed in Claus's catalog start with the designation "O08." In order to give them separate identities, I have added the key in square brackets. (*/2 signifies the second movement (i.e. the fugue) of a prelude-fuge pair).*

[2] Because O08:[C] has less than 30 usable bars, for this composition segments of 25 bars were taken.

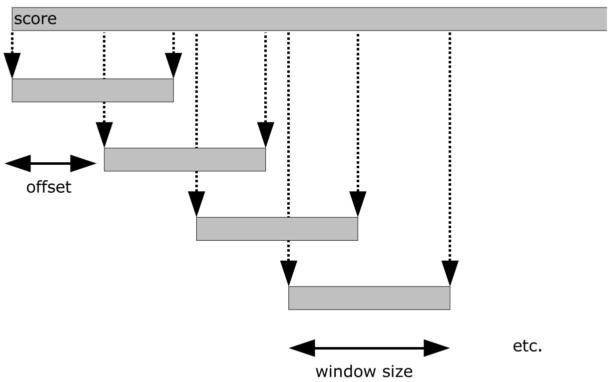


Figure 1. *Schematic view of overlapping segments used in the analysis.*

Some features may be better suited for classification than others. Choosing the "wrong" features may even lead to more confusion. Therefore, Pudil's floating forward feature selection algorithm (1994) has been applied. This algorithm successively adds or removes one or more features in order to optimize a certain criterion.

In order to get an indication of the reliability of a classification algorithm, the error rate is estimated as follows: one composition is removed from the dataset, a classifier is trained on all other compositions, and the data points of the removed composition are classified. After this has been done for all compositions, the error rates are averaged. In this way the dependency of the data points is accounted for. For convenience, I will call this error rate the leave-one-composition-out error rate (LOCO error rate).

Because we are interested in the catalog of J. S. Bach, the styles are evaluated in pairs, each consisting of J. S. Bach and one of the other composers. For each pair the optimal subset of features is selected using the Pudil algorithm. The criterion that is optimized is the LOCO error rate of a nearest neighbor classifier. A nearest neighbor classifier assigns the unknown object to the labeled object that is nearest in the feature space. The advantage of this classifier in the current situation is that no assumption is made about the distribution of the data points. Only local densities are used. To classify a composition, all individual segments are classified by the nearest neighbor classifier.

6 GENERAL FINDINGS

For each pair, the optimal set of features that is selected by the Pudil algorithm is indicated in Table 2, along with the percentage of Bach-segments that has been misclassified and the percentage of segments from the other composer that has been misclassified. To give an impression of the data comparisons, scatter plots in Figures 2a, b, and c show for each comparison the two best musical features as selected by the Pudil algorithm.

Classes	Selected features	Misclassified J.S. Bach	Misclassified other
J.S. Bach, J.L. Krebs	Seconds between parts Thirds between parts Sevenths between parts Dissonance between parts Bars beginning with dissonance	4.5 %	2.1 %
J.S. Bach, J.P. Kellner	Octaves between parts Stepwise resolved suspensions Time-slice stability	0 %	3.2 %
J.S. Bach, W.F. Bach	Perfect fourths between parts Diminished fifths between parts Sevenths between parts Parallel fourths between parts Dissonance between parts Bars beginning with dissonance Pitch entropy Time-slice stability	1.6 %	19.3 %

Table 2. *The selected feature subsets for each of the two-class problems with corresponding loco error rates.*

6.1 J. S. Bach vs. J. L. Krebs

In the case of Krebs, the selected optimal subset consists of 12 features with an overall error rate of 1.5%, but when varying the desired size of the optimal subset, Pudil’s algorithm shows that for sets with more than five features, the error rate decreases only marginally. The only composition that causes troubles with the set of five features is the fugue in G minor, BWV 542/2. 24 of the 80 segments are misclassified, while with the optimal set of 12 features, only one segment is misclassified. Because smaller feature sets are preferable, it is better to take the optimal subset with five features, and accept the partially misclassification of BWV 542/2. Hence, the subset that is indicated in Table 2 is the second best feature subset in terms of error rate, but a better subset in terms of size.

With the found subset, the differences between J. S. Bach and Krebs can be characterized as follows. Bach used more seconds and sevenths and fewer thirds than Krebs, and J. S. Bach's pieces contain more dissonances.

6.2 J. S. Bach vs. J. P. Kellner

For recognizing the styles of J. S. Bach and J. P. Kellner, three features proved to be sufficient. The J. S. Bach segments have more dissonances revolved by step. They also have a steadier rhythm than the Kellner segments. Kellner's O08:06 and O08:[F] utilize more octaves than the pieces by J. S. Bach.

6.3 J. S. Bach vs. W. F. Bach

Eight features are needed for optimal classification. It appears that the error is mainly caused by misclassification of Fk 33 (16 out of 51 segments) and Fk add. 211/2 (27 out of 51 segments). The combination of the selected features is too complex to allow one to characterize the differences between J. S. and W. F. Bach in a few sentences. Apparently, style discrimination for this pair is more difficult than for the other two.

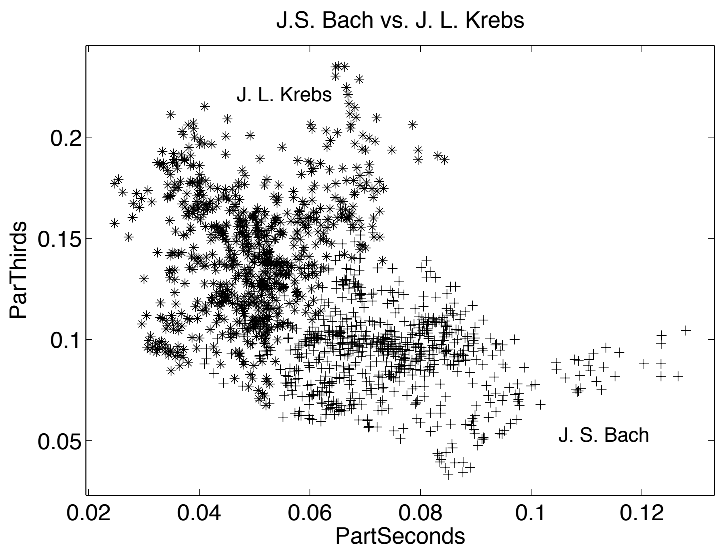
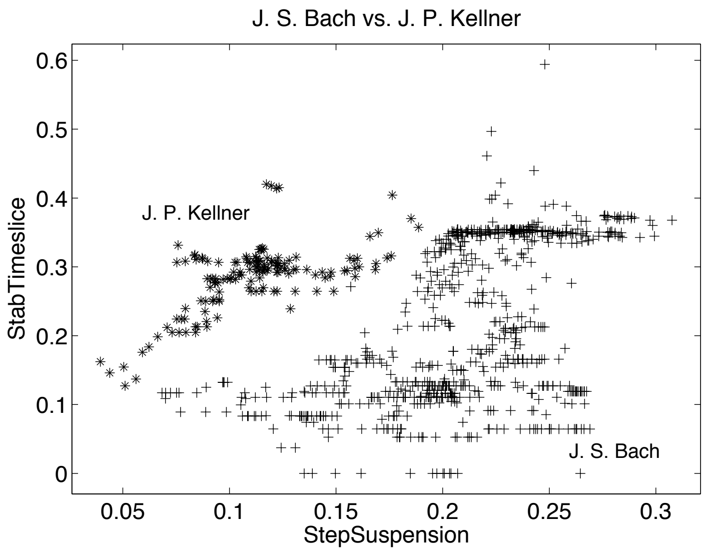


Figure 2(a)*. Projection of the segments onto the planes spanned by the two most important features for J. S. Bach (+) compared to J. L. Krebs (*).*



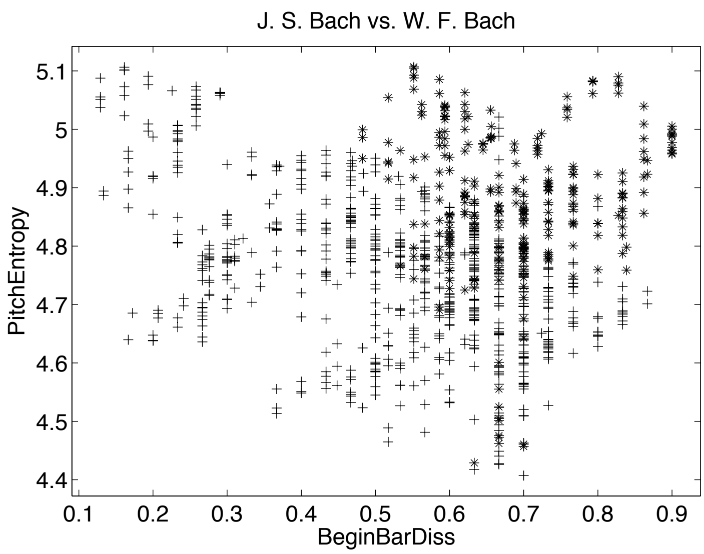


Figure 2, *cont. Projection of the segments onto the planes spanned by the two most important features for (b, upper figure) J. S. Bach (+) compared to J. P. Kellner (*), and (c, lower figure) J. S. Bach (+) compared to W. F. Bach (*).*

7 CLASSIFICATION OF THE DISPUTED WORKS

The classification results for the disputed fugues are shown in Table 3. The comparisons will now be discussed individually, since the sets of parameters which proved to be most significant varied from work to work.

BWV No. of work	**J. S. Bach compared to**	**No. of segments classified as J. S. Bach**
534/2	Krebs	34 / 102
	Kellner	54 / 102
	W.F. Bach	94 / 102
536/2	Krebs	94 / 135
	Kellner	134 / 135
	W.F. Bach	135 / 135
537/2	Krebs	74 / 95
	Kellner	95 / 95
	W.F. Bach	75 / 95
555/2, 557/2, 558/2, 559/2, 560/2	Krebs	5 / 84
	Kellner	61 / 84
	W.F. Bach	84 / 84
565/2	Krebs	24 / 50
	Kellner	46 / 50
	W.F. Bach	50 / 50

Table 3. *Classification results for the disputed fugues. For each fugue the number of segments that are classified as J.S. Bach is shown as fraction of the total number of segments in the piece.*

7.1 BWV 534/2

Although early writers on the organ works of Bach like Philipp Spitta (1916:583), Albert Schweitzer (1955:238) and Hermann Keller (s.a.: 79f) did not esteem the Fugue in F Minor, BWV 534/2, as much as other fugues, the authorship was not doubted. In 1985 David Humphreys rejected this fugue as a composition by J. S. Bach. Dirksen (2000) suggested W. F. Bach as the actual composer. From Table 3 it is clear that the attribution to W.F. Bach is not supported. It is more difficult to adjudicate between J. S. Bach and Kellner. Classification between J. S. Bach and J. L. Krebs points strongly in the direction of Krebs, but the attribution to Krebs is not really convincing. If Krebs had composed the piece, the part of it that is misattributed (33%) is larger than for all involved undisputed fugues by Krebs. This fugue might have been composed by another composer.

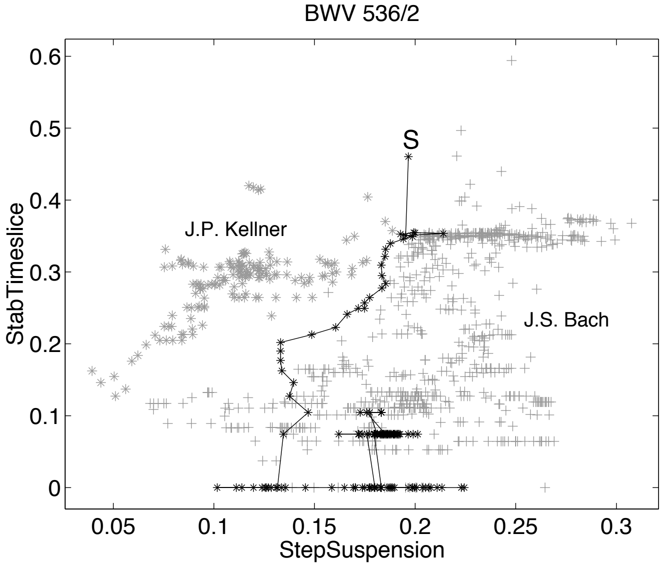


Figure 3. *Projection of the trajectory of BWV 536/2 onto the plane spanned by the two most important features for the pair of composers. The first segment of the fugue is marked by "S".*

7.2 BWV 536/2

A very interesting hypothesis about the fugue in C minor (BWV 537/2) was posed by John O'Donnell (1989). In the earliest source the first 90 bars are written down by Johann Tobias Krebs (1690–1762) and the remaining 40 bars by his son, Johann Ludwig. This is one of the reasons for O'Donnell to suppose that the piece was left unfinished by J. S. Bach and was completed by J. L. Krebs on request of his father, who was copying the score. The classifier assigns the last 13 segments to J. L. Krebs. These correspond almost exactly with the last 40 bars. The trajectory of the piece in the plane spanned by the two most important features (seconds and parallel thirds) is interesting. The trajectory starts in the cluster of J. S. Bach. From bar 60, a second, chromatic theme dominates the fugue. As soon as the segments contain bar 60 or higher, the trajectory goes into the cluster of Krebs, but with a relatively large number of seconds. The following part, in which the chromatic theme dominates all segments entirely, goes outside both clusters. Finally, the trajectory ends in the heart of the cluster of Krebs. A chromatic theme is rare in J. S. Bach's organ fugues. This might explain why the trajectory goes outside the J. S. Bach cluster early. Bach probably changed his strategies by writing more thirds, but Krebs was able to use his "normal" amount of seconds and parallel thirds while composing the last 40 bars. So they treated the chromatic theme in a different way. In any case, the current results support the claim that this fugue was composed by two composers. The authorship of J. L. Krebs for the last 40 bars is likely. See Figure 4.

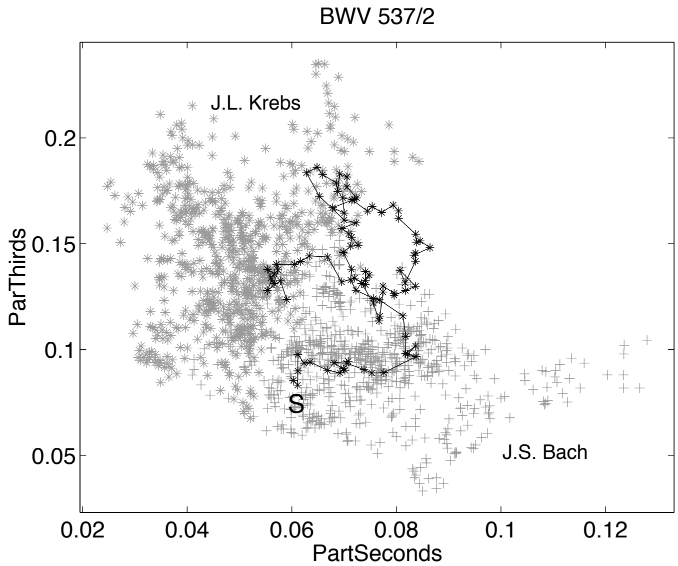


Figure 4. *Projection of the trajectory of BWV 537/2 onto the plane spanned by the two most important features for the pair of composers. The first segment of the fugue is marked by "S".*

7.3 BWV 555/2, 557/2, 558/2, 559/2 and 560/2

These five fugues are part of the *Acht kleine Präludien und Fugen*. The other three fugues of this collection are too short to measure reliable features values (less than 30 bars). Because of the coherence of the group, they are treated as a single composition. The authorship of these eight little preludes and fugues has been discussed a lot. The relatively low quality has been an important reason for this. Several composers are suggested, among them J. L. Krebs (Keller 1937: 67f). But, there is also a rejection of the authorship of Krebs (Tittel 1966). The classification results in table 3 support the rejection of the authorship of J. S. Bach. Also W. F. Bach can be excluded. It can be concluded that from the currently involved composers, these fugues share most the characteristics of the style of J. L. Krebs. But, again, it might be very well possible that they are composed by another composer, whose style is not represented in the dataset.

7.4 BWV 565/2

The case of the fugue in D minor BWV 565/2 is interesting because it is part of the most famous organ work in existence, the Toccata in D minor. Although this piece is known to almost everyone in western society as *the* organ piece by J. S. Bach (especially the beginning), its authorship is disputed, mainly because the style of the work differs so much from all other organ works by J. S. Bach. Several theories have been posed, but it is still an unresolved question. Because the earliest source was written down by J. P. Kellner's student Johannes Ringk, Kellner might be considered a candidate. In an extensive study, Rolf Dietrich

Claus (1998) concludes that Bach cannot be the composer. Neither does Claus make an attribution to Kellner. This is in accordance with the current results as shown in Table 3. The classification of half the piece as J. L. Krebs supports questioning the authorship of J. S. Bach, and in comparison with the style of Kellner, BWV 565 more resembles the style of J. S. Bach. The trajectory is shown in Figure 5. Apart from the first segment, the style is rather consistent under this projection. Although the proportion of dissonances that is stepwise resolved is in accordance with some pieces by Kellner, the regularity of the combined rhythm of all voices is clearly not.

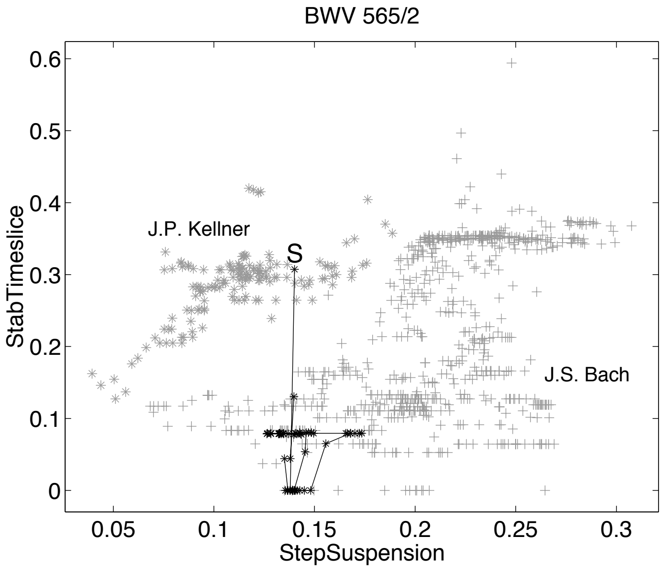


Figure 5. *Projection of the trajectory of BWV 537/2 onto the plane spanned by the two most important features for the pair of composers. The first segment of the fugue is marked by "S".*

8 CONCLUDING REMARKS AND FUTURE WORK

It is shown that the proposed quantitative approach to the recognition of personal styles of composers results in valuable additions to existing authorship disputes (in this case about some of the disputed organ fugues in Bach's catalog). Although the current results do not offer enough evidence to draw final conclusions for these compositions, it is clear that this method is helpful in finding and testing hypotheses about differences in personal styles. Because the available data (scores) are extensively used, these hypotheses are firmly connected to the scores. This is unlike many "traditional" studies, in which proof by example is the best achievable.

In order to interpret results from methods like these, statistical studies should be accompanied with musicological theories about musical style. A possible theory has been offered by Meyer (1996). This should be extended with a theory that predicts which patterns (features) will be important for a specific problem. For compositions that are not strictly polyphonic, a set of relevant features still needs to be identified.

Acknowledgments
Frans Wiering and Jörg Garbers (University of Utrecht, Netherlands) made many valuable comments on the draft. For the software that was written to measure the feature values, the C++ library *CPNView* by Donncha O'Maidin (University of Limerick, Eire) was used. His willingness and support are very much appreciated. For the feature selection and classification algorithms, the implementation of PRTools was used (*http://www.prtools.org*). The encoded datasets are listed and software posted at *http://www.musical-style-recognition.net.*

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