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Author(s): David Huron

Source: *Music Perception: An Interdisciplinary Journal*, Vol. 10, No. 4 (Summer, 1993), pp. 435-443

Published by: [University of California Press](#)

Stable URL: <http://www.jstor.org/stable/40285582>

Accessed: 06/10/2010 18:07

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## Note-Onset Asynchrony in J. S. Bach's Two-Part Inventions

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DAVID HURON

*Conrad Grebel College, University of Waterloo*

Experimental evidence has shown that the perceptual segregation of concurrent auditory streams is enhanced when tone onsets are asynchronous rather than synchronous. Previous research has shown that the amount of onset synchrony is significantly less for polyphonic works than for homophonic works. In this study, an analysis of 15 polyphonic works by J. S. Bach shows that the amount of onset synchrony is significantly less than would be expected by chance, and so suggests that synchronous onsets are intentionally minimized by the composer. The results are consistent with the objective of maintaining the perceptual independence of the polyphonic voices.

### Introduction

Both common experience and empirical research confirm that the temporal coordination of sounds is an important factor in the perception of tonal fusion. Sounds whose onsets occur at the same time are much more apt to be interpreted by the auditory system as constituents of a single sound event. Conversely, sounds whose onsets are uncoordinated in time are likely to be perceived as distinct or separate events (Bregman & Pinker, 1978). In broad terms, onset synchronization may be regarded as a form of amplitude comodulation. Apart from the crude coordination of tone onsets, the importance of correlated changes of amplitude has been empirically demonstrated for much more subtle amplitude deviations. For example, McAdams (1984) and Bregman, Abramson, Doehring, and Darwin (1985) have demonstrated that the coevolution of amplitude envelopes contributes to the perception of tonal fusion.

Depending on the musical goal, tonal fusion may or may not be desired by a composer. If an objective of polyphonic music is to maintain the perceptual independence of the contrapuntal voices, then one might expect

Reprint requests may be sent to David Huron, Conrad Grebel College, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1.

to see evidence that polyphonic composers are reluctant to write synchronous note onsets for concurrent parts or voices.<sup>1</sup> In previous work (Huron, 1989), it was shown that the amount of onset synchrony is significantly less for polyphonic works than for homophonic works. Specifically, in a study of 143 works by several composers, it was shown that a measure of onset synchrony is one of the best factors for discriminating between homophonic and polyphonic musical textures. Although these previous results are consistent with stream segregation theory, a stronger case would show that the lower onset synchrony values in polyphonic works arise because of the active avoidance of synchronous onsets. In this paper, we present a score-based method for measuring onset synchrony and test the hypothesis that onset synchrony is actively minimized in the polyphonic music of J. S. Bach.

### Onset Synchrony

The concept of synchronization raises the question of what is meant by “at the same time?” Under ideal conditions, it is possible for listeners to distinguish the order of two clicks separated by as little as 20 msec (Hirsh, 1959). However, in more realistic listening conditions, onset differences can be substantially greater and yet retain the impression of a single onset. Initial transients for natural complex tones may be spread over 80 msec or more—even for tones with rapid attack envelopes (Saldanha & Corso, 1964; Strong & Clark, 1967). Many sounds have much more gradual envelopes, and in the case of echoes, more than 100 msec between repetitions may be required in order for successive sounds to be perceived as distinct events (Beranek, 1954/1986).

In the case of synchronization of note onsets in music, Rasch (1978, 1979, 1988) has collected a wealth of pertinent data. Ensemble performances of nominally concurrent notes show that onsets are typically spread over a range of 30–50 msec. Moreover, in experiments with quasi-simultaneous musical tones, Rasch has found that the effect of increasing asynchrony is initially to add “transparency” to multitone stimuli—rather than to evoke separate sound images (Rasch, 1988, p. 80). In musical contexts, onset asynchronies must be comparatively large before separate sound onsets are perceived.

Although notes that are notated as having synchronized onsets are by no means performed precisely together, such tones are obviously more likely to promote the perception of tonal fusion than tones that are notated as having

1. In previous work (Huron, 1991a), it was shown that Bach tends to avoid harmonic intervals whose frequency relationships promote tonal fusion.

asynchronous onsets. A difference of a sixteenth-duration at a tempo of 80 quarter notes per minute produces a nominal asynchrony of 187 msec—a delay that is more than sufficient to elicit the perception of separate events. In short, onsets that are deemed “asynchronous” according to musical notation are unlikely to be perceived as synchronous, whereas onsets that are deemed “synchronous” according to musical notation may well be perceived as being synchronous. Thus we can conclude that musical notation provides a useful (although not infallible) source of data for a study of onset synchrony in composed music.

In order to test the hypothesis that polyphonic composers tend to minimize or avoid synchronous note onsets, a study of onset synchrony was carried out on a sample of two-part polyphonic works by Johann Sebastian Bach. Specifically, the sample of works consisted of the 15 two-part keyboard Inventions (BWVs 772–786). There are several possible ways of measuring note onset synchrony. One useful method of measurement is to express the degree of onset synchrony for a given passage as the proportion of synchronous note onsets to the total number of (synchronous and asynchronous) onsets:

$$S = \frac{P}{I+P} \times 100\% \quad (1)$$

where  $S$  is the onset synchrony expressed as a percentage,  $P$  is the number of occurrences of synchronous note pairs, and  $I$  is the number of occurrences of isolated (asynchronous) onsets.

For example, if a work contains 90 synchronous onset points and 10 asynchronous onset points, then the degree of onset synchrony would be 0.9 or 90%. Using this method, onset synchrony measures were made for each of the 15 two-part Inventions. The mean onset synchrony was found to be 44.99% (9.53 S.D.)—however, this value has little meaning by itself because we do not know whether this is less than or more than what might be expected to arise “by chance.”

In order to test our hypothesis, we need to contrast the measured onset synchrony with a similar measure for a control body of music. One way to achieve this is to generate notes for a hypothetical stochastic “work” in which the rhythmic distributions of the voices are identical to the rhythmic distributions of the voices in the original materials. Measures of onset synchrony in the stochastic works can then be compared with measures for the actual works.

In Huron (1991b), an *auto-phase method* was described, which is well suited to the task of providing a control group against which Bach’s compositional activities can be compared. Specifically, an auto phase can be likened to an autocorrelation in which the two voices are shifted with

respect to each other through a complete circle of 360°. Measures of onset synchrony can be taken for each novel configuration as the parts are shifted with respect to each other by some fixed metric division (such as a sixteenth duration). Only when the parts are aligned at zero degrees does their relationship correspond to the original musical score.

The advantage of this method is that each rearrangement preserves the identical durations and within-voice rhythmic order for the two voices. Thus, this method allows us to factor out the effects of duration and within-voice rhythmic order on the proportion of synchronous onsets. All non-zero-degree synchrony measures can be amalgamated to provide a controlled distribution against which the actual proportion of onset synchrony can be compared.

A further control is required in order to eliminate rhythmic variations due to metric position. Note onsets tend to occur with greater frequency in certain metric positions within a measure. For example, Figure 1 shows a histogram for note onsets occurring at different metric positions based on an analysis of a large sample of musical works in simple quadruple meter.<sup>2</sup> Figure 1 represents a single musical measure that has been divided into 32

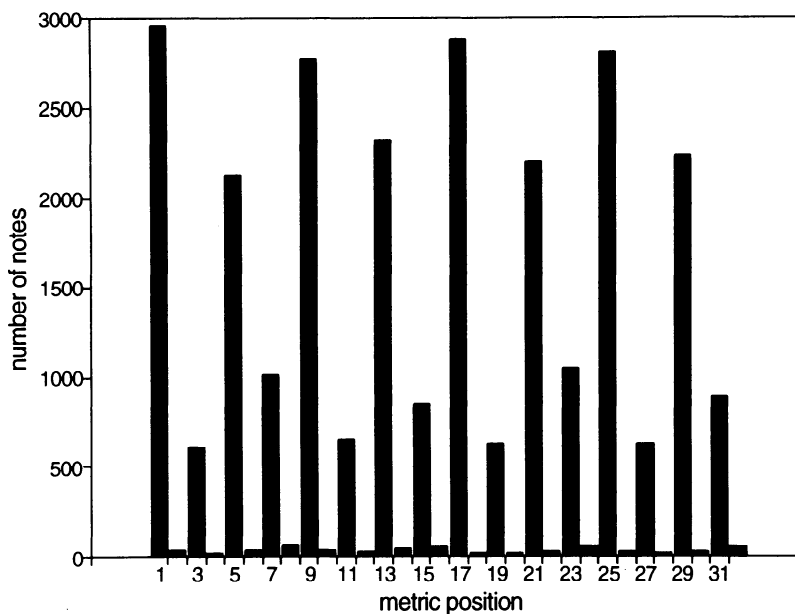


Fig. 1. Metric profile shows the frequency of occurrence of note onsets at 32 metric positions in a measure. Based on a sample of music in simple quadruple meter.

2. The sample consisted of all fugues in J. S. Bach's *Well-tempered Clavier* in simple quadruple meter.

metric positions (comparable to 32nd notes in 4/4 meter). For each metric position, the number of notes whose onsets fall in that position have been graphed. For example, 2956 notes in the sample were found to occur at the beginning of the measure, whereas the onsets of only 33 notes were found to occur at the second thirty-second note position. The metric profile in Figure 1 displays a typical rhythmic hierarchy: the most common onset positions coincide with the four major beat divisions, followed by subbeat divisions, and so forth.

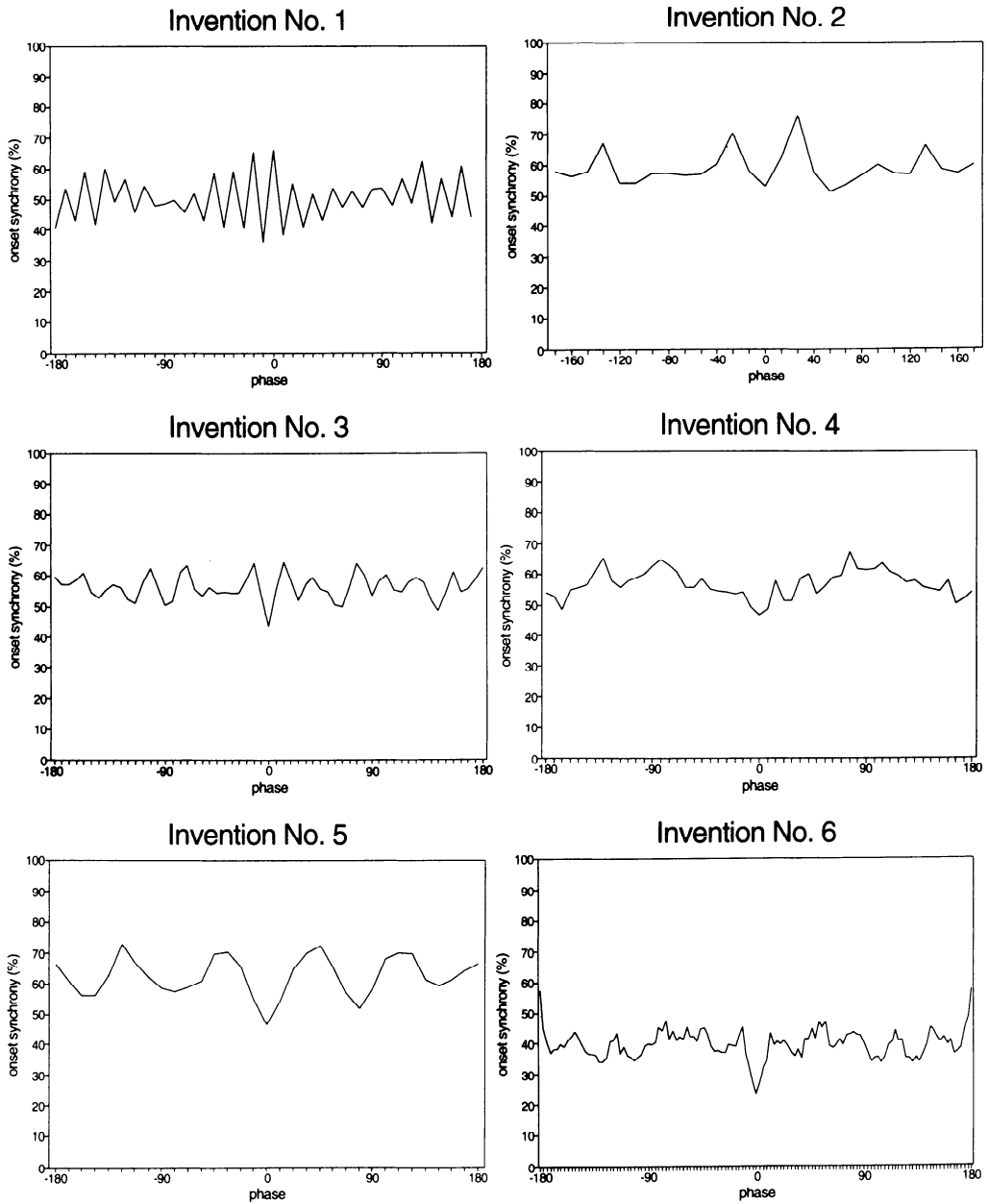
Since note onsets are obviously influenced by metric placement within the measure, it is important for our controls to reflect a similar metrical distribution. To this end, the appropriate step size in our auto phase is the unit of a *measure*. By shifting the voices measure-by-measure, the metric placement of each note is preserved. In effect, the measures for each of the two voices will be systematically permuted and the proportion of coincident onsets calculated for each phase-shifted arrangement.

## Results

Figure 2 shows auto-phase onset synchrony functions for each of the 15 two-part Inventions. The *y*-axis in each figure displays the percentage of onset synchrony, whereas the *x*-axis unravels each of the phase relationships between the two voices. Since the successive phase shifts occur in steps of one measure, the number of points plotted in each auto phase is equivalent to the number of measures in the work.

With the exception of Inventions 2, 8, 14, and 15, the minimum values in the remaining auto-phase functions all occur at zero degrees. For these 11 works, the position of their respective minima indicate that there is no other permutation of the rhythms of the two voices (controlling for duration, rhythmic order, and meter) such that it would be possible to produce less onset synchrony between the parts than occurs in Bach's actual musical arrangement. (In the case of Inventions 2, 8, 14, and 15, the auto-phase values at zero degrees are the second, third, or fourth lowest values found in their respective auto-phase functions.) The probability of encountering such low values by chance is  $p \ll .00001$ . Hence the results are consistent with the hypothesis that Bach is endeavoring to minimize the occurrence of synchronous onsets between the polyphonic voices.

The magnitude of the effect can be seen by contrasting the actual degree of onset synchrony for a given work with the mean value of the corresponding phase shifted controls. Table 1 shows the actual, mean control, and percent reduction from the mean control values for each of the 15 works. On average, the actual onset synchrony is 22.7% lower than the mean for the control values.



**Fig. 2.** Onset synchrony auto-phase functions for the 15 two-part Inventions by J. S. Bach. Values plotted at zero degrees indicate the proportion of onset synchrony for the actual works. All other phase values indicate the proportion of onset synchrony for rearranged music—controlling for duration, rhythmic order, and meter.

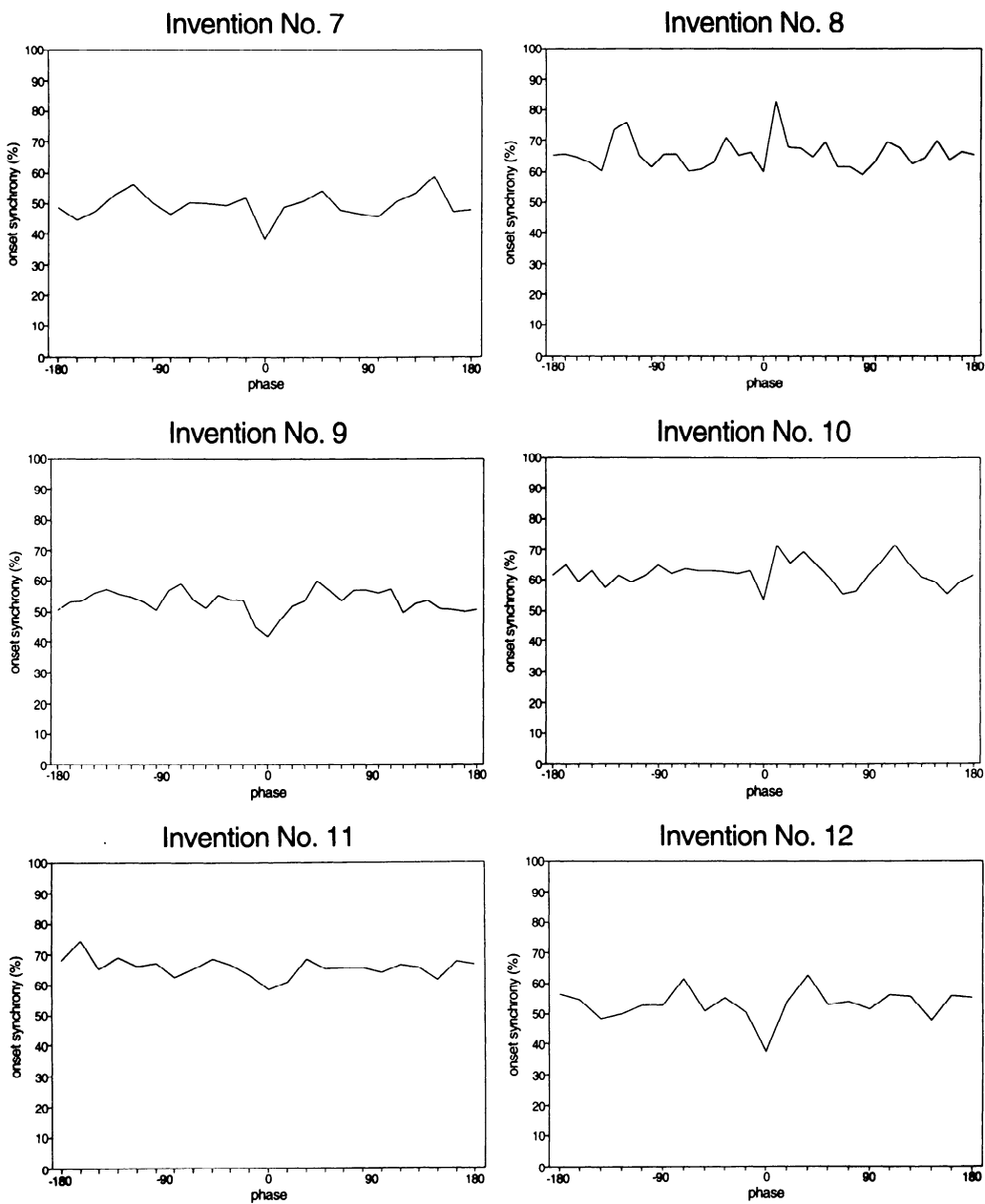


Fig. 2. Continued



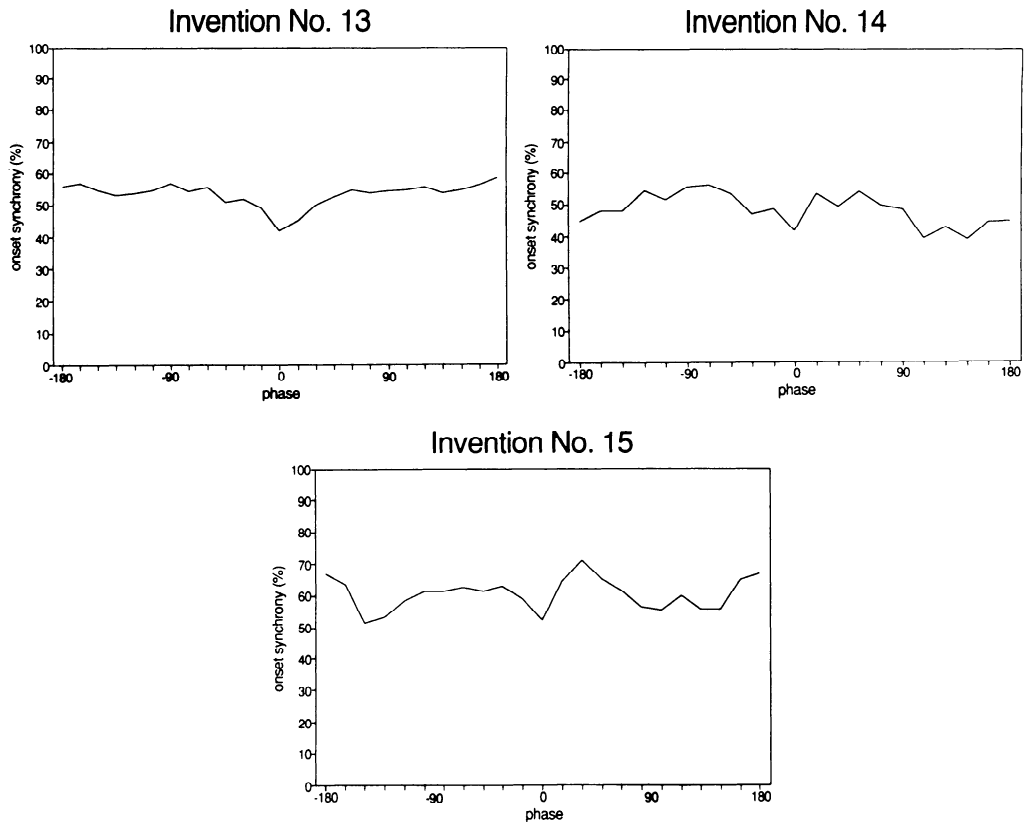


Fig. 2. *Continued*

TABLE 1  
**Comparison of Actual and Control Measures of Onset Synchrony in J. S. Bach's Two-Part Inventions**

Invention	Mean Onset Synchrony (controls)	Onset Synchrony (actual)	Percent Reduction of Onset Synchrony
1	54.5	35.7	34.4
2	63.3	53.6	15.5
3	57.3	43.6	23.9
4	58.2	46.5	20.0
5	63.1	46.7	26.0
6	39.8	23.5	40.9
7	50.0	38.4	23.2
8	68.7	59.7	13.2
9	55.9	41.8	25.1
10	62.4	53.5	14.3
11	66.0	58.2	11.8
12	53.9	37.6	30.3
13	53.7	42.1	21.6
14	52.6	41.8	20.4
15	64.8	52.2	19.4

## Conclusion

In previous research, it has been shown that polyphonic music displays significantly less onset synchrony than other musical genres (such as homophony). In this article, an analysis of the 15 two-part Inventions by J. S. Bach shows that Bach endeavors to minimize simultaneous note onsets between concurrent voices. These results suggest that the lower amounts of onset synchrony found in polyphonic music arise because of explicit compositional efforts to avoid occurrences of synchronous note onsets. If it is assumed that an objective of polyphonic music is to preserve independent perceptual images of the concurrent voices, then Bach's compositional practices are consistent with empirical observations concerning the perceptual fusion of sounds whose onsets are synchronous.<sup>3</sup>

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3. This research was supported in part through funds provided by the Social Sciences and Humanities Research Council of Canada.