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BRIEF REPORT

ECG artifacts and heart period variability: Don't miss a beat!

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Abstract

The impact of artifacts on estimates of heart period variability were evaluated by modeling the effects of missed R-waves and spurious R-wave detections in actual and simulated heart period series. Results revealed that even a single artifact, occurring within a 128-s interbeat interval series, can impart substantial spurious variance into all commonly analyzed frequency bands, including that associated with respiratory sinus arrhythmia. In fact, the spurious variance introduced by a single artifact may be greater than that associated with true basal heart period variability and can far exceed typical effect sizes in psychophysiological studies. The effects of artifacts are not related to a specific analytical method and are apparent in both frequency and time domain analyses. Results emphasize the importance of artifact detection and resolution for studies of heart period variability.

Descriptors: Artifacts, Electrocardiography, Heart period variability, Heart rate, Respiratory sinus arrhythmia

Artifacts in electrocardiographic recordings lead to the spurious quantification of R–R intervals and can result in substantial biases in studies of the chronotropic state of the heart. This problem has been well recognized in the literature, and a number of artifact-detection algorithms have been developed to assist in the identification of questionable heart periods (e.g., Berntson, Quigley, Jang & Boysen, 1990; Cheung, 1981; Linden & Estrin, 1988). With continuing technical developments, it is now possible to acquire huge psychophysiological data sets. Large data sets, however, can make artifact processing time consuming, and a resulting temptation may be to short-cut or bypass artifact processing and editing. An added complexity, with more sophisticated methods for analysis of heart period variability, is that artifact-laden segments cannot simply be deleted from a sequential heart period record because this disturbs the basic time series that is required for analysis.

In view of these considerations, and the increasing applications of heart period variability measures in psychophysiological studies, an important question arises as to the quantitative impact of unresolved artifacts in the heart period data. Although previous reports have indicated that artifacts may introduce substantial errors in measures of heart period variability (Xia, Odemuyiwa, Gill, Malik, & Camm, 1993), the issue has not been examined systematically. The present study evaluated the effects of artifacts on measures of heart period variability by introducing both missed beats and spuriously detected R-waves into known series of simulated and actual heart period data. Results reveal that even a single heart period artifact, occurring within a 2-min recording epoch, can lead to errors of estimate of heart period variability that are considerably larger than typical effect sizes in psychophysiological studies.

Method

Analyses were based on two sets of interbeat interval (IBI) data, one comprised of simulated heart periods and the other derived from actual heart period records. The advantage of simulations is that the frequency components of variance can be controlled, and the precise characteristics of the input signal are specifiable. Actual heart period series were also tested to ensure the generality of the results obtained by the simulations. Two samples of each of the simulated and real IBI data sets were employed, one with a higher and one with a lower level of basal heart period variability. Each IBI series was approximately 2 min (128 s) in duration, which is a common recording length for studies of heart rate variability, and within the 1–5-min epochs generally recommended (Berntson et al., 1997; Task Force, 1996).[1]

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[1] The effects of artifacts with different epoch durations can be estimated from the present results. The contribution of a given deviant data point to the total variance is directly proportional to the number of data points in the sample. Because the sum of the spectral densities is equal to the total variance (within the limits of filtering and detrending, which can remove some variance), the effect of a given artifact within IBI series of different durations will be inversely proportional to the epoch length. Thus, the effects of a single artifact as determined in the present study would be approximately doubled for a recording epoch of 64 s, and approximately halved for an epoch of 256 s. These values are approximate because they apply to total spectral power. Although artifacts yield a broadband increase in spectral power, this power may not distribute entirely equally across the frequency bands.

Simulated IBIs

A series of simulated IBIs was derived from a continuous pure sine wave function designed to model a rhythm within the typical respiratory frequency band (~12/min). Simulated IBI series were derived by sampling this sine wave function at a frequency of 1.2 Hz (corresponding to a heart rate of 72 bpm), yielding approximately six IBI values per respiratory cycle. The actual sine wave frequency was slightly less than 12/min (0.198 Hz) to avoid identical repetitive sequences of simulated heart periods derived from precisely corresponding points on successive sine wave cycles. For the high variability IBI sequence, the sine wave modulation was ±100 ms (peak to peak), around a basal heart period of 833.3 ms (72 bpm). The low variability series was similarly derived, except that the amplitude of modulation was ±50 ms.

Real IBIs

Two additional series of actual heart periods were derived from archival baseline recordings from adult subjects. These data sets were judged to be artifact-free based on a quantitative artifact-detection algorithm (Berntson et al., 1990) and a careful visual examination of the records. As for the simulated series, the two actual IBI series were selected to sample differing levels of overall heart period variability.

Artifacts

Two classes of artifacts (missed beats and extra beats) were systematically introduced into each of the four IBI data sets (simulated vs. real × high vs. low variability), at random points in the data epochs. Missed beats were created by deleting the R-wave detection nearest the random point. Artifactual R-wave detections were introduced at that point, with the constraint that they lie within the middle 10–90% of the relevant IBI.[2] Although these artifacts were introduced experimentally, their effects are precisely the same as actual artifacts. The sole contribution of the experimental procedure was the determination of where the artifact occurred within the data series.

Two basic approaches were employed for the primary analyses. First, we evaluated the effects of single artifacts occurring at various points in the data samples. Second, we examined the effects of multiple artifacts in a given heart period record. For the first set of analyses, a single missed beat or a spurious beat was introduced at one of five different random locations within each of the IBI datasets. Because artifacts yield highly deviant heart period values, their occurrence at the extreme ends of an IBI series would introduce linear trends that could not be removed by detrending, without introducing offsets at the beginning and end of the data. Consequently, artifacts were limited to the middle 75% of each IBI series and were not introduced at immediately adjacent beats.

The second set of analyses examined the effects of multiple artifacts (0–5) occurring within a given IBI series. For these analyses, the five artifacts defined above for each base IBI series were progressively introduced, and their cumulative effects were evaluated.[3]

Data Analysis

Heart period variability within distinct frequency bands was analyzed by two common methods. The primary approach was by spectral analysis (Cooley-Tukey fast Fourier transform), with a secondary analysis by the moving polynomial filter (MPF) method of Porges (Porges & Bohrer, 1990), as implemented in the MxEdit program (Version 2.21; Delta Biometrics, Bethesda). Three frequency bands were analyzed: (a) a high-frequency band representing typical respiratory frequencies (0.15–0.4 Hz), (b) a midfrequency band centered around the 0.1 Hz Mayer wave (0.05–0.15 Hz), and (c) a low-frequency band (0.008–0.05 Hz).

For spectral analysis, the 128 s of IBI values were time sampled at 2.0 Hz to yield the requisite time series, and data were detrended to remove the DC component and any linear trend in the data. A 10% cosine taper was applied to the beginning and end of the series, the data were analyzed, and the sum of the spectral densities was derived over the relevant frequency bands. The MPF method was also employed to derive a time domain estimate of heart period variability (Porges & Bohrer, 1990). For both approaches, results were expressed as the natural log of the variance, as recommended (Porges & Bohrer, 1990; Riniolo & Porges, 1997). To avoid assumptions of parametric methods, experimental effects were evaluated by nonparametric tests.

Results and Discussion

The general approach is illustrated in Figure 1, which shows the high variability simulated IBI series (with 0, 1, and 5 missed-beat artifacts) and the resulting spectral density functions. The simulated respiratory rhythm yielded a sharp peak in the spectrum at 0.2 Hz, modeling a pattern of high-frequency heart period variability associated with respiratory sinus arrhythmia. The introduction of missed beats led to a progressive spurious elevation in the 0.2-Hz peak and the appearance of broadband noise and smearing of the spectral distribution.

Effects of Single Artifacts

The overall effect of artifacts was to enhance power in all frequency bands, with missed beats having a greater effect than spurious R-wave detections. Table 1 illustrates the effects a single artifact at various loci within each (128-s) IBI series. Effects on mean heart period were minimal, but considerably larger effects were apparent on variance estimates, such as the standard deviation and especially the spectral estimates of heart period variability. There were only minimal differences in the effects of artifacts at different loci within the IBI series, as shown by the small standard deviations of the measures of variability (Table 1).

Friedman's nonparametric tests confirmed significant overall differences between the missed-beat, extra-beat, and artifact-free datasets for the standard deviation of heart periods, $\chi r^2(df = 2) = 38.1$, $p < .001$, and for each of the three frequency bands of heart period variability, all $\chi r^2(df = 2) > 38$, $ps < .001$. For each of these dependent measures, Dunn's tests revealed that both the extra-beat and the missed-beat values were significantly greater

[2] Because many acquisition/analysis systems preclude detection of a second R-wave for a period of time after a prior detection, this constraint was imposed to yield estimates of the effects of artifacts that would be broadly representative.

[3] Because both types of artifacts can occur in the same record, we also examined the effects of combinations of artifact types within a single IBI series. Although there was some effect of the relative positions of the artifacts, for the most part, the effects of combined missed-beat and extra-beat artifacts was approximated by the sum of the independent effects of the artifacts. The effects of a single missed beat and a single extra beat in the two actual IBI series, for example, yielded an estimate of spectral power in the high-frequency band of 8.50 and 7.62 (for the high and low variability series, respectively) versus 8.52 and 7.67 predicted by the independent contributions of the artifacts.

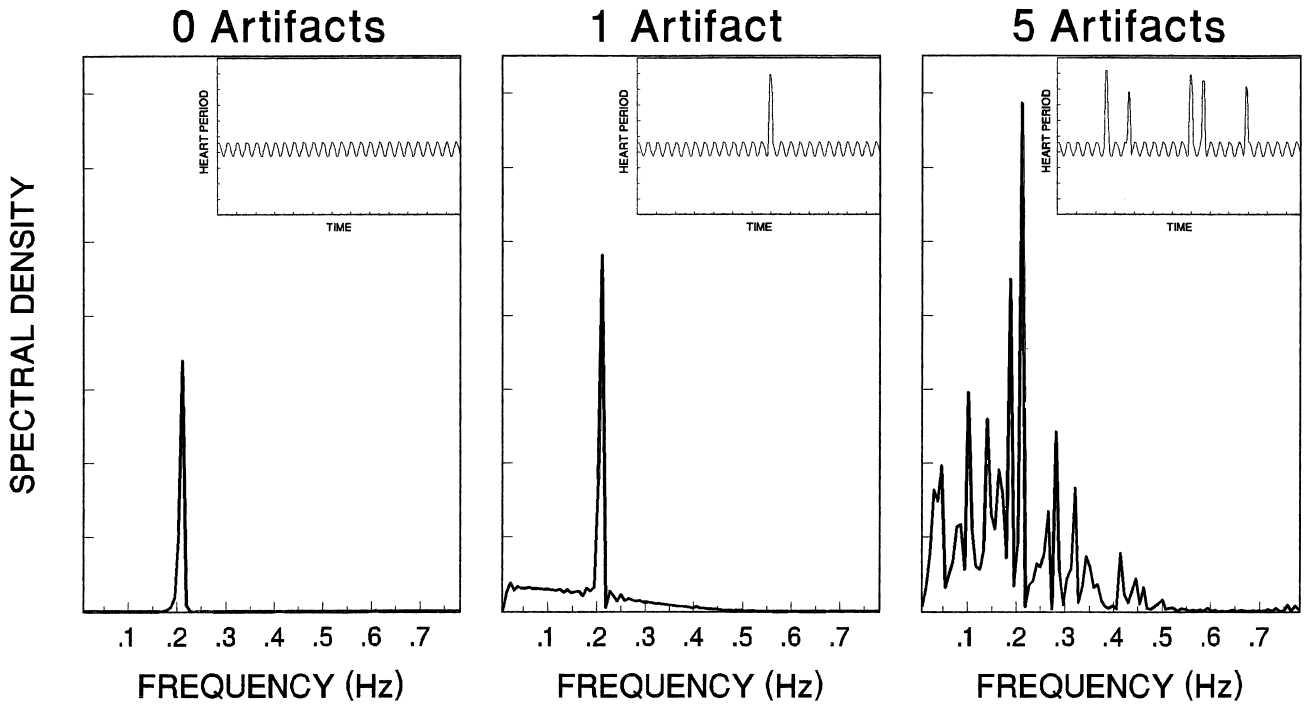

Figure 1. Effects of artifacts on spectral power for the simulated data set modeling a ±100-ms respiratory modulation of heart period at 0.2 Hz. Inserts depict the simulated interbeat interval series, entailing 0, 1, or 5 missed beats, and the main panels illustrate the resulting spectral density plots derived from fast Fourier transform analyses. Introduction of artifacts leads to a progressive increase and broadening of spectral power.

Table 1. *Effects of Single Artifacts on the Mean and Standard Deviation of Estimates of Heart Period Variability*[a]

	Heart period				Heart period variability frequency band					
	M		*SD*		High		Mid		Low	
IBI Series	Base[b]	Artifact	Base	Artifact	Base	Artifact	Base	Artifact	Base	Artifact
Missed beats										
Simulated	833	839	71.2	100.3	8.25	8.95	0.54	7.79	0.00	7.11
(100 ms)		(0.0)[c]		(6.3)		(0.23)		(0.25)		(0.27)
Simulated	833	839	35.6	73.7	6.86	8.39	0.00	7.73	0.00	7.03
(50 ms)		(0.0)		(4.3)		(0.22)		(0.16)		(0.20)
Real-high	1073	1083	63.4	119.4	7.16	8.99	6.68	8.81	6.12	8.18
variability		(0.0)		(7.0)		(0.08)		(0.29)		(0.40)
Real-low	851	857	37.1	77.0	5.37	8.17	6.04	7.93	5.48	7.11
variability		(0.0)		(5.3)		(0.18)		(0.32)		(0.31)
Overall	898	904	51.8	93.2	6.91	8.62	3.32	8.07	2.90	7.36
Extra beats										
Simulated	833	828	71.2	87.9	8.25	8.37	0.54	5.31	0.00	4.49
(100 ms)		(0.0)		(2.5)		(0.07)		(0.36)		(0.44)
Simulated	833	828	35.6	61.8	6.86	7.19	0.00	5.29	0.00	4.53
(50 ms)		(0.0)		(4.2)		(0.10)		(0.27)		(0.27)
Real-high	1073	1064	63.4	98.4	7.16	7.72	6.68	7.13	6.12	6.44
variability		(0.0)		(6.9)		(0.14)		(0.14)		(0.35)
Real-low	851	845	37.1	63.6	5.37	6.57	6.04	6.46	5.48	5.78
variability		(0.0)		(4.7)		(0.13)		(0.17)		(0.25)
Overall	898	891	51.8	77.9	6.91	7.46	3.32	6.05	2.90	5.31

[a]Values in parentheses represent the sample standard deviations ($n = 5$) of the estimates derived across the various artifact locations. [b]Value of the artifact-free base IBI series, into which artifacts were introduced. [c]Regardless of its location within the series, a missed beat leads to an equivalent increase in mean heart period because the sample epoch contains exactly one less beat than the artifact-free series. Similarly, any single extra beat yields an equivalent decrease in mean heart period. Consequently, the variance estimates for mean heart periods is zero.

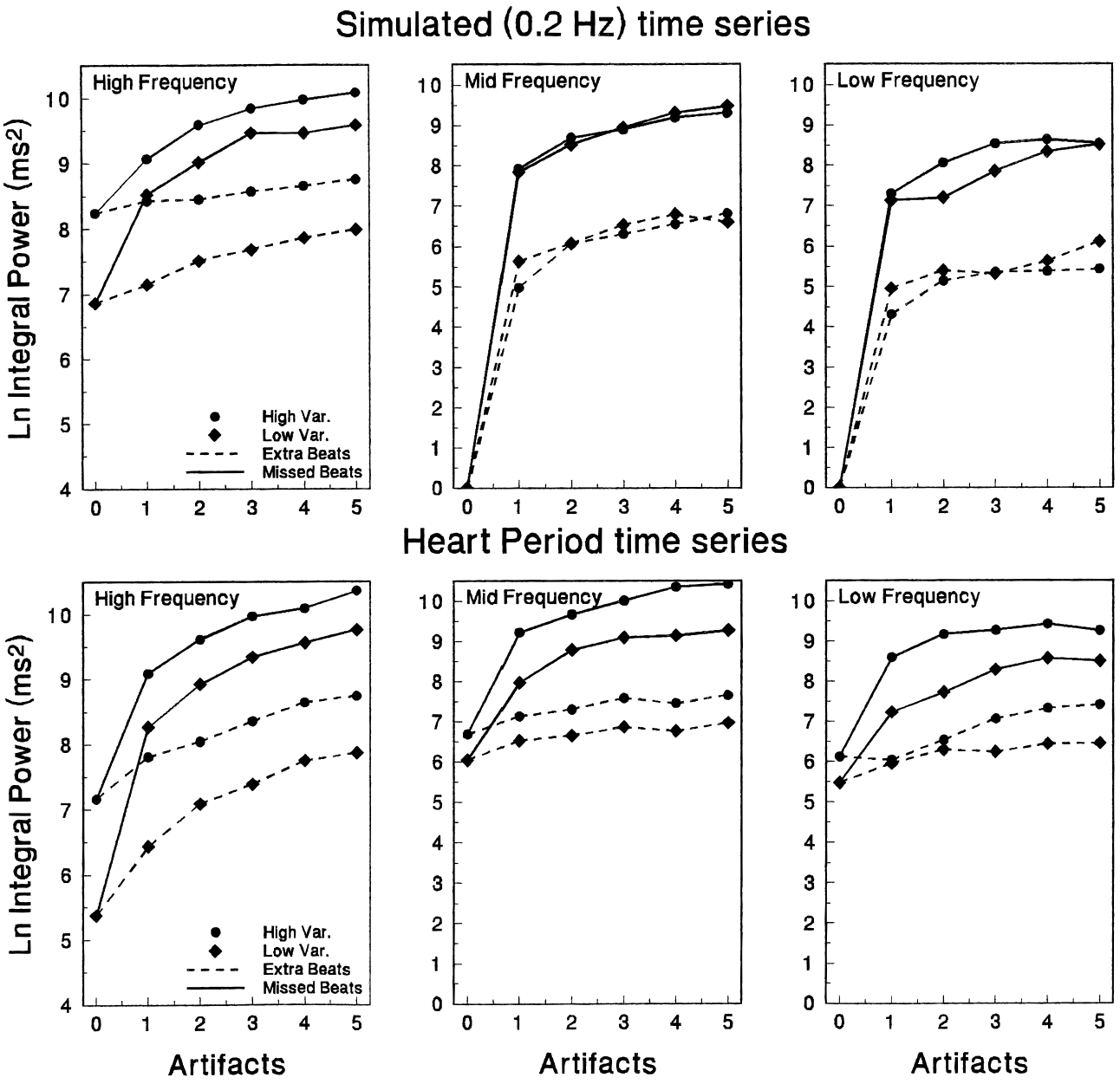

Figure 2. Effects of artifacts on the integrated spectral power within three frequency bands (high = 0.15–0.40 Hz, middle = 0.05–0.15 Hz, and low = 0.008–0.05 Hz) for simulated and actual interbeat interval (IBI) series. Each panel depicts the effects of missed beats and spurious R-wave detections into artifact-free IBI series, with higher or lower levels of basal variability. The corresponding solid line (missed beats) and dashed line (extra beats) functions converge at the 0-artifact level, because they were derived from the same IBI series. By design, there was no measurable power in the mid- and low-frequency bands for the simulated data sets in the absence of artifacts. For illustration, the ordinates for the lower-frequency plots are different from those for the high-frequency band.

than for the artifact-free dataset and that the effects of missed beats were significantly larger than those of extra beats.

The effects of a single artifact are dramatic. A single artifact can increase the estimate of high-frequency variability by almost 3 natural log units (see missed-beat artifacts for the real, low-variability IBI series in Table 1). This is a large bias relative to typical experimental effect sizes in psychophysiological studies (often in the range of 0.5–1.0 Ln). The influence of artifacts is especially apparent in the simulated IBI series, which have no appreciable power in the mid- and low-frequency ranges in the absence of artifacts. A single artifact resulted in the appearance of 4–7 log units of spurious variance in these mid- and low-frequency bands.

For all frequency bands, the effects of artifacts were uniformly larger for the four IBI series with the lowest basal variability than for the four with higher levels of variability (all Mann-Whitney Us ≥ 118, ps $< .03$). This appears to be largely attributable to the log scaling of the variance estimates because

the effects of artifacts were not significantly different across basal levels of variability for nontransformed data. This is an important finding in view of the recommendation for natural log transforms in analyses of rhythmic sinus arrhythmia (Porges & Bohrer, 1990; Riniolo & Porges, 1997) because one cannot rely on difference scores to subtract out what may be an equivalent distribution of artifacts across conditions.

Missed beats uniformly yielded larger effects than spurious R-wave detections, probably because a missed beat introduces an average IBI deviation equal to the mean heart period, whereas the expected deviation from an extra beat is only half the mean heart period (although there are two deviant beats in this case). Even spurious R-wave detections, however, resulted in sizeable biases in estimates of heart period variability.

Effects of Multiple Artifacts

The impact of multiple artifacts was evaluated by the successive introduction of one to five artifacts into the IBI series. As illustrated in Figure 2, increasing the number of artifacts led to a progressive increase in spectral power in all frequency bands; for all IBI series and frequency bands, Friedman's χr^2s($df = 4$) >36, ps $< .001$. Without exception, the effect of increasing artifacts was to monotonically increase *total* spectral power for every IBI series. There were some minor, local exceptions to this trend within specific frequency bands (e.g., see the high-variability, extra-beat function in the lower left panel of Figure 2). These exceptions were largely attributable to harmonic peaks that were located near boundaries of frequency bands. With the introduction of an additional artifact, a slight lateral shift in these peaks sometimes resulted in a reduction of power in one frequency band and a corresponding increase an adjacent band.

In accord with the results for single artifacts, missed beats yielded appreciably greater spurious increments in power than extra beats for each frequency band (Table 2), all Wilcoxon Ts ($N = 8$) = 36, ps $< .01$. The largest increment in power estimates was seen with the introduction of the first artifact, with subsequent artifacts having progressively smaller effects. For each IBI series and frequency band, the increment in spectral power with the introduction of the first artifact was significantly greater than that associated with the second artifact, all Wilcoxon Ts ($N = 8$) $\geq$ 32, ps $< .03$. There was also a trend for decreasing effects with higher numbers of artifacts, but these differences no longer achieved significance. To some extent, the greater effects of the initial artifacts was due to the log scaling, although the same trend was also apparent in the untransformed data.

The results outlined above are not attributable to the use of frequency domain analyses because comparable results were obtained with the MPF time domain method (Porges & Bohrer, 1990). Analyses with the MPF method, paralleling those outlined above, yielded an essentially identical pattern of results. Correlations between the heart rate variability estimates derived from spectral and MPF methods, over all frequency bands, were .98 $\pm$ .01 ($p <$ .001) for both the simulated IBI series and the actual IBI data.

Table 2. *Effects of Multiple Artifacts on the Mean (SD) of Heart Periods*

	Number of artifacts					
IBI Series	0	1	2	3	4	5
Missed beats						
Simulated	833	839	844	850	856	861
(100 ms)	(71)	(105)	(132)	(150)	(164)	(174)
Simulated	833	839	844	850	855	861
(50 ms)	(36)	(79)	(101)	(126)	(141)	(154)
Real-high	1,073	1,083	1,092	1,101	1,111	1,120
variability	(3)	(129)	(166)	(194)	(218)	(235)
Real-low	851	857	862	868	874	880
variability	(37)	(78)	(107)	(130)	(144)	(156)
Extra beats						
Simulated	833	828	823	817	812	807
(100 ms)	(71)	(88)	(101)	(116)	(124)	(132)
Simulated	833	828	822	817	812	807
(50 ms)	(36)	(60)	(78)	(89)	(101)	(115)
Real-high	1,073	1,064	1,056	1,048	1,039	1,031
variability	(63)	(92)	(120)	(136)	(153)	(174)
Real-low	851	845	840	834	829	826
variability	(37)	(65)	(80)	(99)	(109)	(115)

Summary and Implications

The present analyses reveal that even a single artifact can contribute substantial spurious broadband power in estimates of heart period variability and that this bias may far exceed typical effect sizes in psychophysiological studies. Although most researchers are aware of the potential contamination from artifacts in physiological measures, the notable magnitude of effects on measures of heart period variability warrants emphasis.

Some patterns of artifacts may yield violations of the assumption of stationarity for frequency domain analyses, and tests of stationarity are to be encouraged (Weber, Molenaar, & van der Molen, 1992). This is a complex issue, however, because violations of stationarity in actual heart period data are probably the rule rather than the exception (Grossman, 1992a, 1992b; Porges & Bohrer, 1990; Weber et al., 1992), and moderate violations may not seriously compromise analyses (Grossman, 1992a, 1992b). It is important to recognize that biases introduced by artifacts are not limited to violations of stationarity with spectral methods. Effects of artifacts were virtually identical for the time domain method of Porges and Bohrer (1990) and were clearly apparent even in simple measures of variance such as the standard deviation. Alternative methods, such as autoregressive modeling, can at least partly exclude aperiodic influences during analysis and hence may be less sensitive to occasional artifacts (Kay & Marple, 1981; Kitney & Darvish, 1995). Regardless of the analytical method, however, results of the present study indicate that artifacts cannot be ignored in studies of heart period variability.

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