MOVING WITH AND WITHOUT MUSIC: SCALING AND LAPSING IN TIME IN THE PERFORMANCE OF CONTEMPORARY DANCE

CATHERINE J. STEVENS
University of Western Sydney, Australia

EMERY SCHUBERT AND SHUAI WANG
University of New South Wales, Australia

CHRISTIAN KROOS AND SHAUN HALOVIC
University of Western Sydney, Australia

TIME-KEEPING AMONG DANCERS WAS INVESTIGATED by measuring a dancer's movement in the presence and absence of music. If an internal clock was at work, then change from the ideal would manifest as scaling—consistently faster or slower unaccompanied performance; if time differences were due to lapsing, then sections from the with-music condition would be deleted, or material would be inserted into the no-music condition. Motion was recorded during ensemble performances of a four-minute choreographed piece with and without music. The median of 24 markers in the height dimension was analyzed for scaling and lapsing. Twenty percent of the variance was accounted for by sporadic scaling. Lapses—insertions and deletions—accounted for nearly all the speeding up—10.45 of 14 s. As in musical performance of memorized material, lapsing rather than scaling accounted for timing variations. Automation of lapsing and scaling detection has application in the analysis of music and dance time series data.

Received August 26, 2008, accepted January 6, 2009.

Key words: time-keeping, memory, dynamic time warping, uniform time scaling, felt time

DANCE IS AN ANCIENT AND UBIQUITOUS form of human expression and communication. In contemporary dance the major medium is movement, deliberately and systematically cultivated for its own sake, with the aim of achieving a work of art. Movement material that is created, performed, or observed engages motor and kinesthetic processes (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005) and leads to cognitive and affective reactions. Contemporary dance shares with other art forms the possibility of being viewed either as nonrepresentational, nonsymbolic, formalist, or of being representational or symbolic in some sense. At one extreme, contemporary dance comprises movement pure and simple, investigating how weight and force interact with time and space (Cunningham, 1968; Gardner, 1993; Vaughan, 1990), requiring no support from music, no visual background, no plot. At the other extreme, dance has been regarded as the termination, through action, of a certain kind of symbolic transformation of experience (Hanna, 1979), or as "an image of dynamic life" (Langer, 1953, p. 175). Across the gamut, dancers and choreographers use the body's motion and stillness to sculpt shapes and patterns in space and time (Stevens & McKechnie, 2005).

Dance generally is created through bodily explorations in the medium of movement itself (Foster, 1976; Grove, Stevens, & McKechnie, 2005; Limon, 1955; Sachs, 1937; Stevens, Malloch, McKechnie, & Steven, 2003), with new phrases improvised and refined, often in silence. Thus, contemporary dance often is not composed to fit or accompany a musical score. The choreographer and dancers work in silence with only breath and foot- or body-impacts producing the auditory soundscape. Where dancers have worked with each other for extended periods, there is a palpable sense of anticipation, synchrony, or "felt time."

In the present study, we begin to investigate the mechanism that underlies dancer time-keeping and synchrony. The first aim was to scrutinize the performance of a short piece that is in development involving a group of three young dancers. Motion capture data recorded from one of the dancers was analyzed to identify underlying processes of scaling (compression or expansion), and memory lapses (deletions or insertions). A second aim was to develop methods of identifying these underlying time-keeping processes in dancers where the accuracy of timing is good but there are also some asynchronies. These methods of analysis and associated time-keeping concepts have application to time-series data recorded in a range of domains in music and dance, and solo and ensemble performance and perception.

One way to examine time-keeping processes while a new work is in development is to systematically

Music Perception VOLUME 26, ISSUE 5, PP. 451–464, ISSN 0730-7829, ELECTRONIC ISSN 1533-8312 DOI:10.1525/MP.2009.26.5.451

manipulate the presence and absence of the accompanying, nonbodily soundscape. Motion of a dancer can then be recorded under two conditions—with and without music. In the present experiment and to maximize ecological validity, these conditions were run as a live performance in the presence of an audience of 40 people. This exploratory study is a first step in recording dancer motion in a theatre with an audience. The opportunity arose for an in situ experiment with agreement from the dancers to dance with and without musical accompaniment. The dancer whose motion was captured was also the choreographer. On the one hand, the presence of three dancers in the space might reduce the possibility of errors in serial recall of movements while, on the other hand, inaccuracies in one dancer may elicit the insertion or deletion of movement by other dancers in an effort to resynchronize with the rehearsed dance score.

Scaling and Lapsing as Indicators of Time-Keeping in Dance Performance

Variation in length of a choreographed dance can be underpinned by at least two mechanisms. If a miscalibrated internal clock is the dancer's time-keeping mechanism then any change in timing from the ideal would manifest as scaling; that is, faster or compressed performance across the work, or alternatively an expanded, stretched, or slower performance across the work, relative to the ideal. This is comparable to 'uniform time scaling' in pattern recognition (Fu, Lau, & Wong, 2008; Hetland, 2004). Alternatively, if sections of the dance jump to other sections (suddenly or otherwise) with omissions and/or insertions of material, then a change in timing will manifest as lapses. In pattern recognition research this is comparable to 'dynamic time warping' (Dixon & Widmer, 2005; Last, Kandel, & Bunke, 2004). We do not propose that the two mechanisms are mutually exclusive, and in fact will argue that they may be interconnected, but their separation is psychologically meaningful.

Two rudimentary time-series methods of analysis are described here to identify time-keeping mechanisms as indicated by the pattern of asynchronies/variations that occur over the course of performing a dance piece in the presence and absence of music. The method is sample-based and automatic rather than phrase-based in an effort to infer time-keeping mechanisms as objectively as possible from live performance data. Further, we propose to keep our analyses in the time domain, in a departure from analytic techniques applied to problems where two similar time-series are compared (e.g., Dixon & Widmer, 2005). Following this preliminary analysis, further investigation and validation using laboratory-constructed stimuli may be conducted under more controlled conditions.

Aim, Design, and Research Question

The aim was to investigate whether a dancer in a no-music condition performs a dance work identically to when the work is danced to music. The dependent measure is the duration of the dance. Dance material is recorded using movement sensors on the dancer's body. We ask whether there is a difference in durations of the dance performed under the two conditions and speculate on causal scaling and lapsing mechanisms.

Method

Participant and Materials

Three dancers performed the choreographed work. One of the choreographers was also one of the dancers and was the participant who wore a black lycra bodysuit onto which were sewn reflective markers. The choreographer/dancer was 16 years old and started dancing at 5 years. In the past three years he performed in professional dance film and live productions. The dancer performed within a demarcated area, 5 m × 5.25 m. There were 24 reflective markers in all, including reflective tape affixed to parts of the dancer's body that were exposed. The left and right markers were placed on: ear (2), top and bottom of shoulder blade (4), top of shoulder (2), top of femur (2), elbow joint (2), wrist joint (2), hip joint (2), knee joint (2), ankle joint (2), foot (2); collar bone and base of sternum served as two reference points.

The dance was *Reactional Movement*, a new work choreographed by Emma Batchelor and James Batchelor for performance in a program of works at the then Australian Choreographic Centre (now QL2 Centre for Youth Dance). The dancer/choreographer created some of the movement material, with a musical track in mind; it was then taught to the other dancers and practiced. Other parts were created collaboratively with the dancers improvising together and then locking in successful phrases of movement from that process. The dancers learned the movement initially without music. When the choreography was familiar, it was rehearsed with the music. The dancers had rehearsed the piece without music but it had not been previously performed without music. The work with musical accompaniment had been performed for a live audience on two previous occasions.

According to its choreographers, *Reactional Movement* is a response to music, movement, and space. It is about responding to situations without direct communication while also exploring the freedom of movement. In *Reactional Movement*, as in contemporary dance generally, multiple dancers are performing in different regions of the space and producing different dance movements. (See Appendix for a description of the dance and dancer activity.) The total duration of the dancer's movement was 4 minutes. The nonbodily soundscape that accompanied the dance work during the with-music condition was *Mysta-Lilli Pilli Drive* from the album *Digital Manipulation* by FourPlay and was played from a CD.

Equipment

The motion of the dancer was recorded using 10 Vicon cameras: 4 × MX40 cameras set on a 15 foot high rig positioned directly over the performance area and 6 × MX3 cameras set on 8 foot high tripods. The camera sampling rate was 100 fps. A digital camera (Sony HandyCam HCR-30E) was used to record each live performance. The data were down-sampled to 20 Hz to attenuate the presence of high frequency noise. All subsequent analyses were conducted using Matlab.

Procedure

The dancers were asked to perform the piece as they would normally, first in silence and then with the musical accompaniment. In both conditions, the marked up dancer moved first followed by the other two dancers. The performances took place in a black box theatre at the Australian Choreographic Centre in Canberra, Australia before an audience of 40 people.

Identifying and Modeling Scaling and Lapses

Identification and Modeling of Scaling

The simplest form of analysis is to compare the duration of the two conditions, and to determine whether the same sequence of choreographed movements was produced in both conditions with identical timings. However, comparison of total duration can be done in different ways. The two simplest are (1) to calculate the time difference of the two lengths and (2) to calculate the ratio of the two lengths. In psychophysics, according to Weber's law differences are perceived as a ratio of the two (in this case time) lengths (Brannon, Libertus, Meck, & Woldorff, 2008). However, such a calculation also has psychological implications from the perspective of performer action. In the with-music (WM) condition, the dancer is time-locked to the music. Extra cues are provided by the beat and section of the music that tells the dancer when to commence a trajectory, when to end a movement phrase, and so forth. To match this, in the no-music (NM) condition the dancer might need some mental image of the music (Halpern, 2001). Generation of the tempo of the piece could be modeled as an internal oscillator or metronome (Geissler, 2000). If the clock driving the dance movements was calibrated precisely with the tempo of the music used in the WM condition (and there were no errors), we would expect a veridical performance in the NM condition. Therefore, by dividing the duration of the NM condition by the duration of the WM condition, we would obtain an estimate of the calibration of the dancer's internal clock. A ratio of one would indicate veridical performance. A ratio of less than 1 indicates that the performance is faster in the NM condition relative to the WM condition (time compression). Veridical or close to veridical timing has been reported when a musician imagined a piece of music compared to performing it (e.g., Langheim, Callicott, Mattay, Duyn, & Weinberger, 2002; Repp, 1999), though we cannot be certain that this, in effect, scaling factor of 1, transfers to the dancers who are not the producers of the music.

Further, there may be another mechanism in operation. If the dancer does not match the serial sequence of dance phrases through omissions of intended movements or insertions of unintended movements in the NM condition, analogous to the insertion and deletion of notes in music sight reading and language reading tasks (Luce & Pisoni, 1998; Palmer & Pfordresher, 2003), we also would expect a difference in the timing of the NM condition with respect to the WM condition. We refer to these additions or deletions as 'lapses,' and they may be caused by memory lapses or by adjustments made to environmental circumstances.

We do not argue that scaling and lapses are necessarily independent. Indeed, mathematically they are not. But they are psychologically distinct processes. While scaling appears to be easily determined by examining ratios, as described above, lapsing is more complex to identify and model (O'Shaughnessy, 2008). In this paper we wanted to apply a simple time-series technique to detect lapses. However, modeling both lapsing and scaling at the same time increases the complexity of the analysis because the two mechanisms do not combine in a linear manner—scaling is a multiplicative process, and lapsing is an additive process. We therefore will attempt to identify the presence or absence of the two mechanisms (scaling and lapsing) separately.

To identify lapses in the NM condition relative to the WM condition, we needed to step through the sequence of the dancer's position data looking for matches and mismatches in body configurations

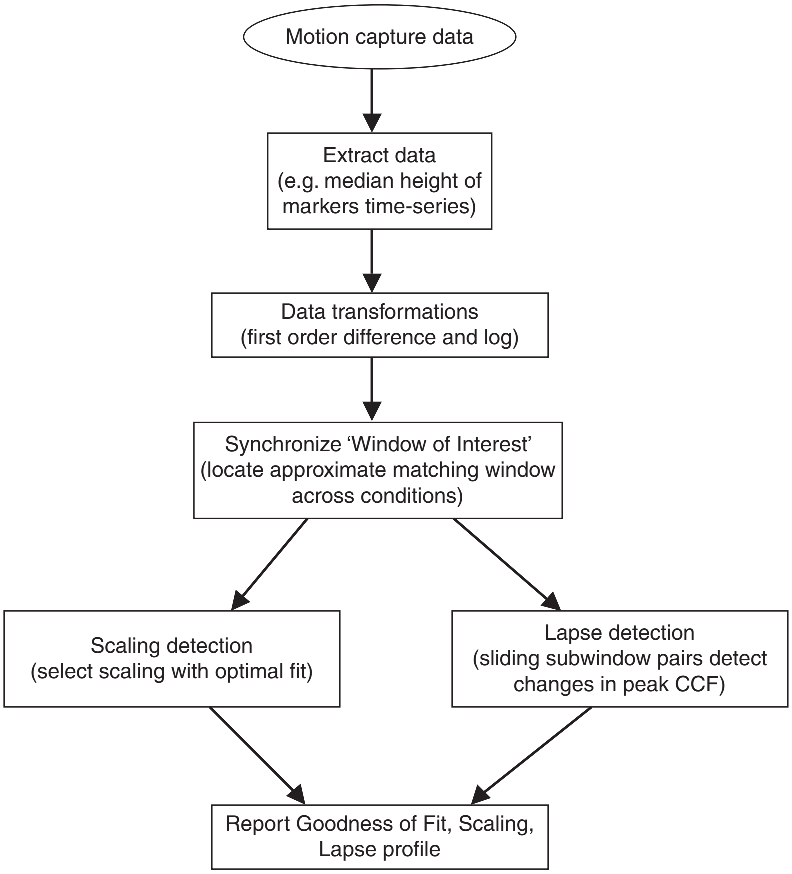

FIGURE 1. Procedures taken to detect lapses and scaling between WM and NM motion capture data.

between the conditions. The following section describes how we identified and modeled lapses.

Identification and Modeling of Lapses

A summary time-series of the dancer's vertical positions was produced by generating the median of all the *z*-axis (vertical) marker positions. The median was used instead of the mean because it is less sensitive to outliers caused by missing marker recordings and noise, each of which may occur due to occlusions, unwanted reflections, etc. The choice of the vertical dimension for analysis was arbitrary, but also informed by the interesting bending over (contraction) and rising movements[1] (release) that were performed by the marked dancer. We anticipated interesting and informative variability in this *z* dimension.

We refer to the time-series of the median vertical movement in the with-music condition as the WM series and the median vertical movement in the no-music condition as the NM series. We generated a copy of the WM series that will henceforth be referred to as the 'residual WM.' The residual WM series will have identified lapses modeled out, which could involve deleting sections of the series, or inserting blanks into (or 'padding') the series. If the process is successful, the residual WM series will resemble the NM series, and the resemblance will be evaluated by its goodness of fit statistic. This statistic is determined by how well the residual WM series predicts the NM series using the coefficient of determination, R^2, as described by Nagelkerke (1991).

Figure 1 shows stages in the analysis. Data transformations involved differencing and log transformation of WM and NM. Differencing was used to reduce serial correlation in the data sets (Schubert, 2002). The log transform reduced the bias in the correlation processes that cause normalization of large values in the motion data.

---

[1] In this paper we use the term 'movement' and 'position' interchangeably, although it is important to note that movement implies the first derivative (rate of change) of position over time.

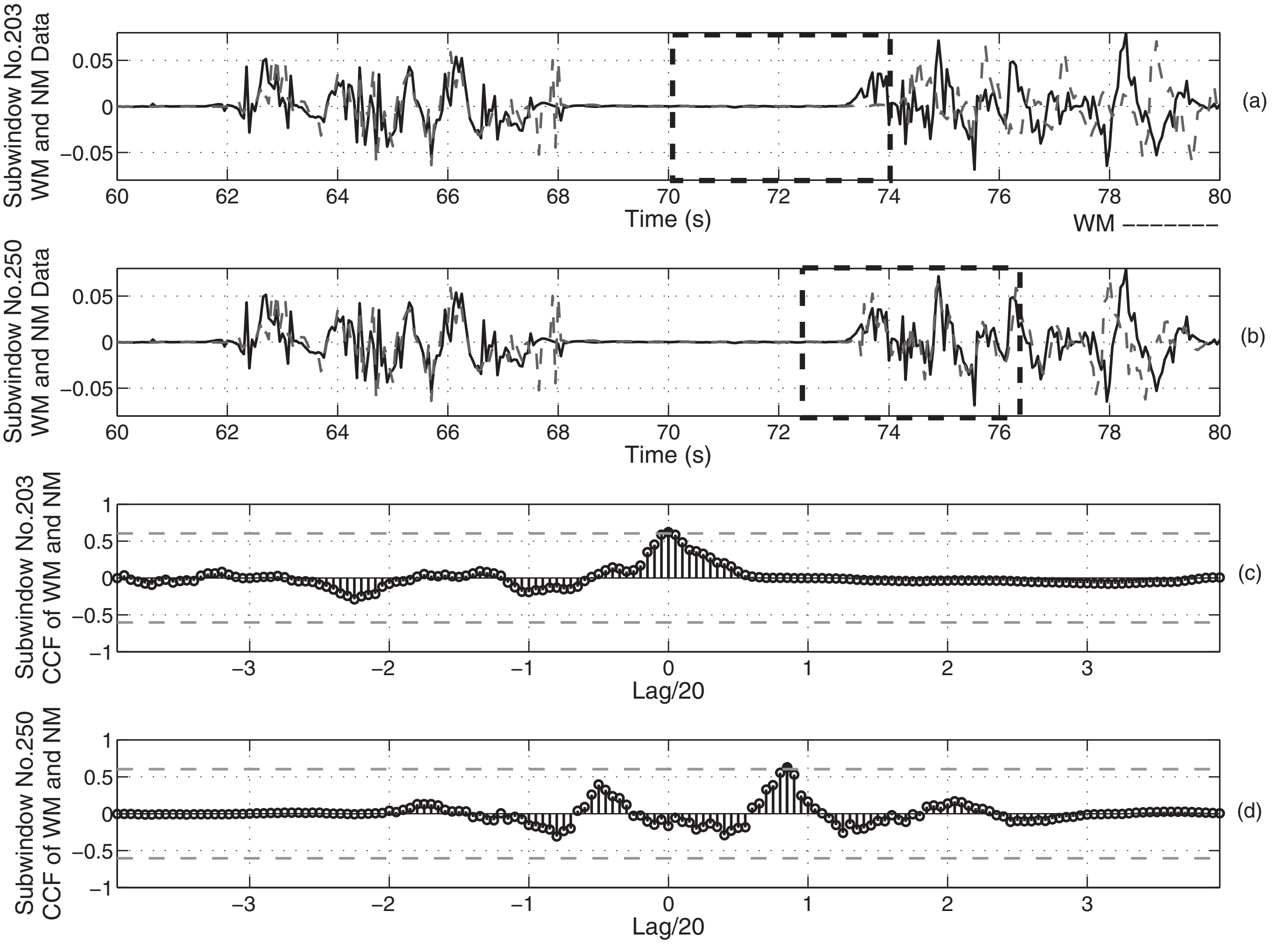

FIGURE 2. An example of lapse detection and modeling: (a) shows the evolving residual WM time-series (dashed line) and the NM (solid line) time-series for the given WOI (Window of Interest) and the 203rd subwindow (SW) indicated by the dotted rectangle; (b) plots the same NM time-series and the evolving residual WM time-series where a lapse has been identified within the 250th SW and modeled out; (c) shows the CCF of the NM and the residual WM time-series within the 203rd SW; (d) shows the CCF values of the NM and the residual WM time-series within the 250th SW just before modeling out the lapse. Notice that in (b) the two series are more closely matched than the two series in (a). This is because a lapse was detected by the CCF in (d) of the paired subwindows in (b) at the point in time shown (note that between (a) and (b) 47 subwindows [2.35 s] had elapsed). The peak of the CCF changes from a lag of 0 in (c) to a lag of +18 lags or 0.9 s in (d). This indicates that the WM series has an additional 0.9 s inserted with respect to the NM series which is therefore removed in the evolving residual WM series, hence making it better resemble the NM series (b). In other words, in the NM condition, a deletion is assumed to have occurred. The sign is changed to indicate removal of 'time' from the residual WM series. The time and −0.9 s value of this lapse is appended to the lapse profile shown in Figure 5.

The analytic approach consisted of breaking the WM and NM series into windows of interest (WOI). The window length was 20 s (400 points at a sampling rate (f_s) of 20 Hz),[2] Thus, the first WOI for the WM series covered the first 20 s of WM condition movements, and the first WOI of the NM series also covered the first 20 s of NM condition movements. The two WOIs were 'synchronized' by aligning them after peak crosscorrelation lag was identified in the Cross Correlation Function (CCF). The CCF indicates the correlation coefficient (output value) between two time-series at various shifts (lags) of one series with respect to the other. The shifts are typically small (sample by sample) time increments. Within this WOI, a smaller 'subwindow,' set to 4 s (80 points at $f_s = 20$ Hz), scanned through the NM WOI and performed CCFs with the corresponding WM subwindow of the synchronized WOI.

The peak CCF lag was located for a subwindow pair. The WM series was lagged with respect to the NM series (Figure 2). As the subwindow pairs progressed in time through the series, the peak lag value was

---

[2] Window of Interest (WOI) length was actually 20.05 s (401 points) to allow a midpoint in the window. Reference is made to a 20 s WOI for ease of reading.

inspected. If the peak lag changed, a lapse identification was assumed. For example, if the 203rd subwindow comparison produced a peak CCF at lag 0, and this remained the peak lag for the next 46 subwindow steps, but in the 250th subwindow the peak CCF lag suddenly jumped to a lag of +18 points (0.9 s), then we assumed that a lapse had been identified. The serial time at which this lapse occured (250th subwindow of the current WOI) was recorded, and the lapse was modeled out. A positive lag (as in the present example) indicated that an extra 0.9 s of time existed in the evolving residual WM series relative to the NM series. Therefore, to better match the NM series, 0.9 s was deleted from the residual WM series (cf. Figure 2b). This is an example of a lapse that seems to have resulted in the dancer jumping ahead in time in the NM condition relative to the WM condition. Since part of the dance was deleted it was recorded as a negative value in the lapse profile. When the lag jumped to a negative value, it meant that the WM residual had time added to it (we used zero padding), and this insertion was recorded as a lapse of positive value.

The criterion for accepting a change in peak lag was that the value of that correlation coefficient be outside a confidence limit of the CCF. This limit was set to .2907. This lapse identification process continued for each stepped subwindow within the WOI. The subwindow step size was one sample (0.05 s). When the subwindow reached the end of the first WOI (0 to 20 s), the second NM WOI was selected (10 to 30 s of the NM condition), and the corresponding WM window was selected. We used overlapping windows with half window step sizes relative to the NM series to ensure that there would be no gaps between WOI in the WM series. A gap may have been caused by the WOI synchronization process that might lead the WM WOI to best match with the NM WOI further forward in time because the WM series happened to be longer than the NM series. Then the lapse detection process continued for this WOI, and the residual WM series was appended. When a lapse was located at the same time by overlapping windows, the average lapse value was recorded.

We used windows of interest rather than the entire time-series because the subwindow comparisons across the two conditions needed to be locked in, to reduce the chances of spurious crosscorrelations with parts of the two series that were actually unrelated. We tried several other approaches to deal with this synchronization issue, but this was a simple method that produced reasonable results. The subwindow itself could not be too long (in time) because we needed to capture fairly small lapses. Large subwindow sizes could subsume small lapses. Again, this subwindow size was determined after some experimentation. The moving subwindow within window of interest approach produced a workable analytic technique.

Results

Overall Time Difference Between Conditions

The duration of the NM condition was 258.5 s and the WM condition was 272.5 s. The median height time-series for both conditions are shown in Figure 3, and they are shown as raw data, and transformed with first order difference and log base 10. If scaling alone was the mechanism attributed to the shorter NM performance, it would be shorter by a factor of 0.0514, or 5.14%. The NM condition is the duration of the WM condition scaled by a factor of 0.9489. However, if the primary mechanism was lapsing, the NM condition would be identified as ending 14 s sooner than the WM condition. That is, overall, 14 s of deletions occurred in the NM condition compared to the WM condition. We now explore which mechanisms provide the best explanation of the difference in time between the two conditions.

Scaling

If we assume scaling as being the main underlying psychological process driving the dancer's execution of the choreography we would expect to see each WOI exhibit roughly the same amount of scaling. If scaling varied as the work unfolded it would be an indicator of a miscalibrated internal clock. In addition, variations could be due to lapses and error. For the scaling analysis we assume these to be negligible, though we will assess the success of the analysis.

A 5 s window was selected in the NM series and through the synchronization process described above, the best nearby match of a nominal 5 s WOI was selected in the WM series. This window was then progressively time stretched and time compressed to unity in increments of 0.001 starting from a trial scaling factor of 0.700 and 1.500 respectively.[3] With each trial scaled WM window and corresponding NM window, the peak crosscorrelation was calculated and stored, and the trial scaling factor at which the maximum of these peaks occurred was the reported scaling factor for that

---

[3] The 'resample' function in Matlab was used to implement scaling. See The MathWorks, www.mathworks.com/access/helpdesk/help/toolbox/signal/, accessed November 26, 2008.

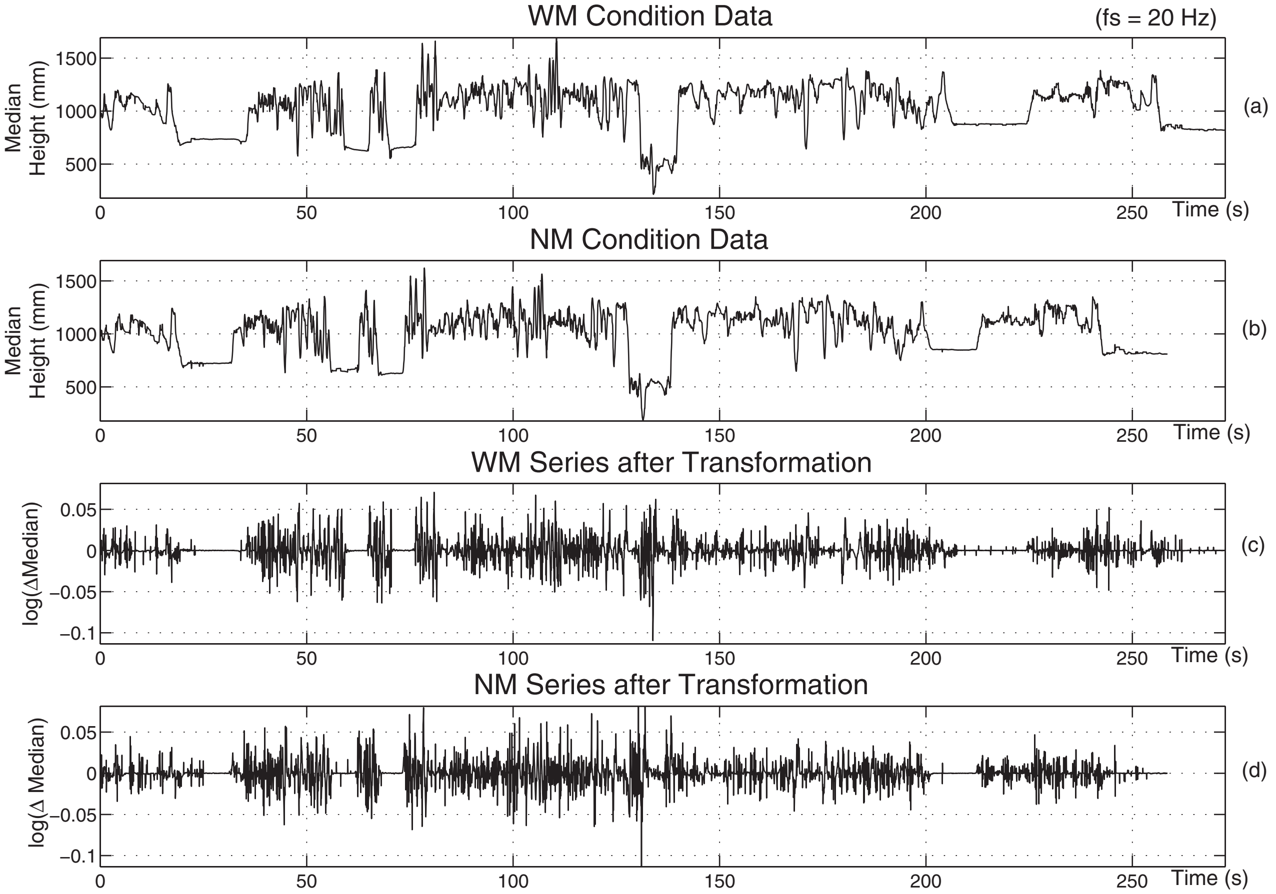

FIGURE 3. Median height time series in WM and NM conditions, with and without transformations. 'Δ' represents first-order differencing, and 'log' is the logarithm transformation to the base of 10.

window. The process was repeated with the next 5 s WOIs stepped at half the window size, 2.5 s (50 points at $f_s = 20$ Hz), along the NM series.

The median of the reported scaling factors was 0.997 with lower quartile at 0.886, and upper quartile at 1.110. The goodness of fit for this scaling calculation was 0.1953, about 20% of the variance. This suggests that scaling is not the only mechanism at play in the NM condition and appears to have little if any overall explanatory power. Indeed, the variation in amount of scaling in different parts of the dance provides an argument against the view that dancers have a simple miscalibrated internal time-keeping clock, and is consistent with literature on imagining memorized music. According to the present analysis, on the whole, the internal clock seems to keep near veridical time (median scaling is close to 1), but some sections of the dance speed up and others slow down. This is demonstrated in Figure 4, where the scaling value calculated for each WOI is plotted over time. Overlayed on the same plot is the goodness of fit estimate for each WOI and the smoothed curve calculated by taking the median of the five surrounding points at each WOI scaling value. The smoothed curve indicates the variability of the scaling as the dance without music unfolds. It seems to begin with some faster sections (scaling less than one) and periods of slowing down (scaling greater than one) appearing sporadically. In addition, the longer scaling bars in Figure 4 are generally not clustered together like those nearer or less than scaling values of one, and the goodness of fit statistics, indicated by small diamonds in Figure 4, are small for nearly each of these larger 'scaling spikes.' This leads us to suspect that the windows identified as slow (large scaling) are unreliable. Thus, while the median value is close to unity, we suspect that some scaling is taking place, and that this scaling is variable (not uniform), but on the whole probably near unity or slightly lower, consistent with the initial, overall scaling analysis reported above. The low goodness of fit values are attributed to lapsing and error. We therefore turn to an analysis of lapsing.

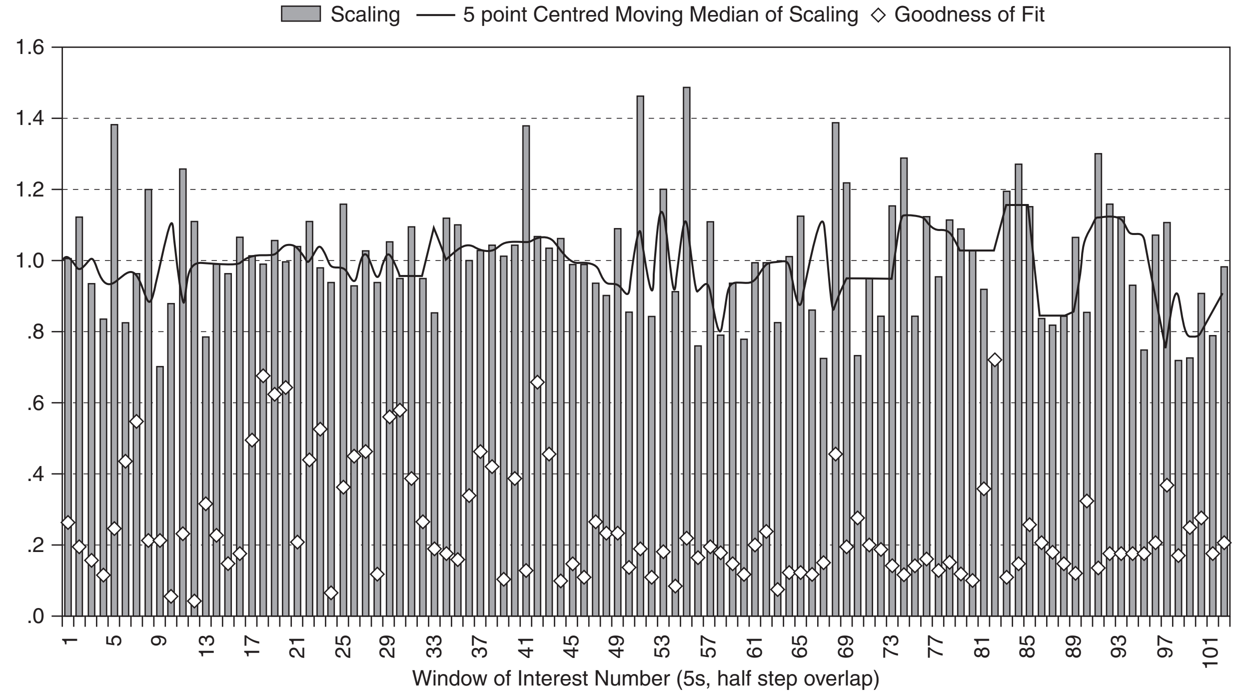

FIGURE 4. Scaling profile. Scaling values in NM condition with respect to WM condition for 5 s long WOIs.

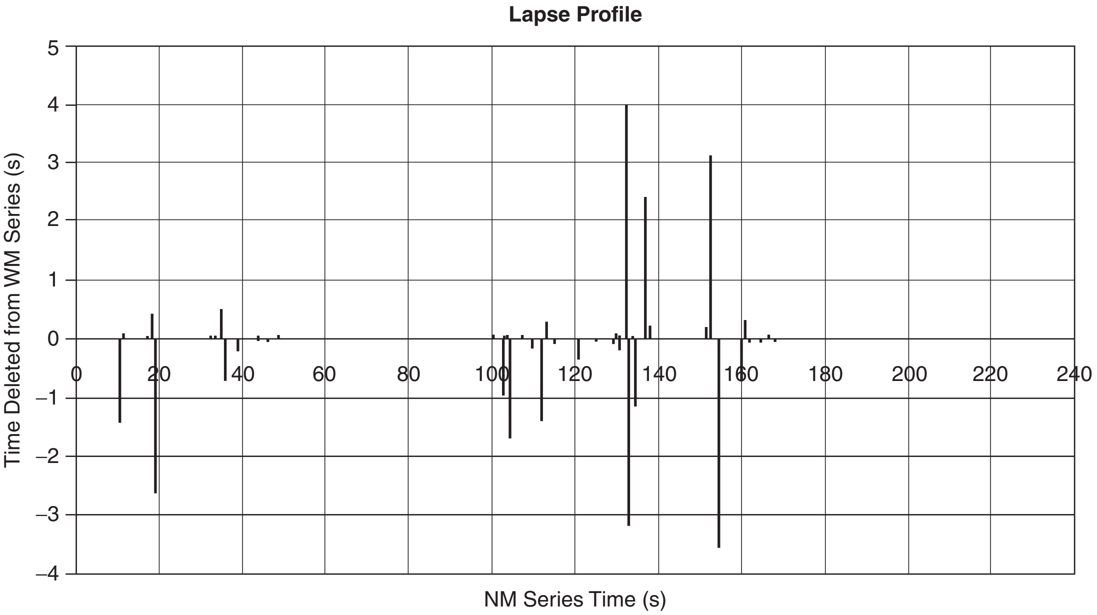

FIGURE 5. Lapse profile. The profile is interpreted as the value of the bar being the amount of time taken out of the WM series in producing the residual WM series at the time indicated on the x-axis (using the time of the residual WM series) that produces the best match with the NM series. A positive lapse indicates an insertion made in the WM series so that it better resembles the NM series. A negative lapse indicates a deletion of material from the WM series so that it better resembles the NM series. The sum of all the lapses provides an estimate of the amount of time gained or lost due to lapsing. In this analysis 4 s subwindows were used within 20 s WOIs. For each subwindow analysis, changes in peak correlation were identified if they occurred above a confidence interval threshold of 0.2907. Only lapses are shown from WOIs where the goodness of fit statistic was greater than 0.2. The sum of the 55 shown lapses is –10.45 s (i.e. an overall 10.45 s deleted in the WM series made it better resemble the NM series).

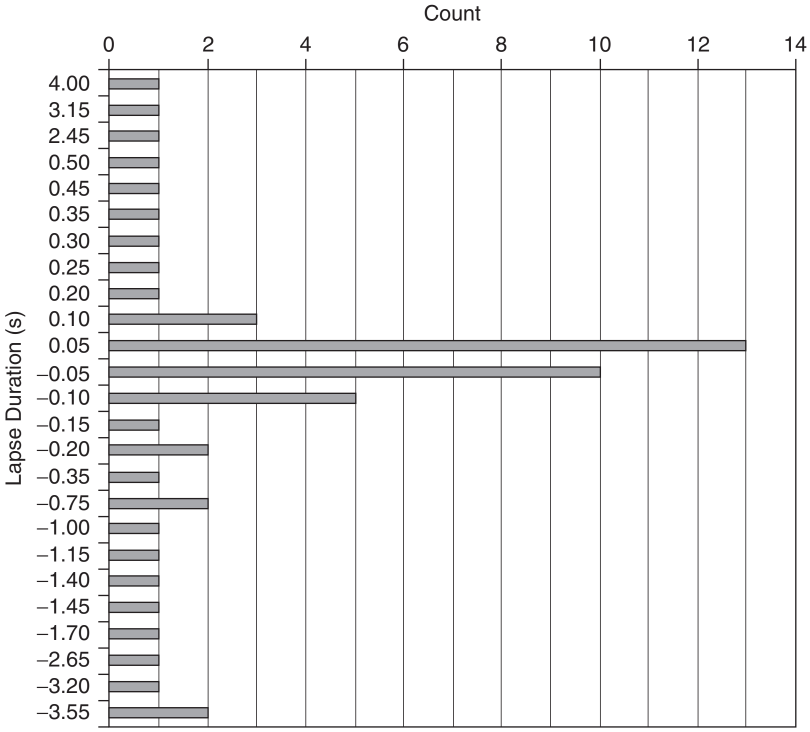

FIGURE 6. Frequency of each detected lapse duration.

Lapsing

The lapse profiles were generated showing the location of the alleged lapses in the NM series (based on the residual WM series) and the duration of each lapse. Lapses were detected in both directions (insertions and deletions) as shown in Figure 5. Some are detected earlier in time in the NM series than the otherwise optimally matching section of the WM series (displayed as negative lapses because 'extra' time was identified in the residual WM series which, when taken out, better resembled the NM series. See Figure 2 for an example). Some appeared later in the NM series than the otherwise optimally matching sections of the WM condition. We checked the points in the video recording where the lapses were detected in each condition to confirm that there was a lapse noticeable across the conditions at those points.

By adding each of the lapse times together, we rendered an estimate of the amount of time that was lost or gained due to lapsing across the entire duration of dance. In our analysis, we estimated −10.45 s of accumulated lapses. The negative sign indicates that overall more deletions (rather than insertions) were made in the NM condition relative to the WM condition. By considering only those WOIs that explained 20% or more of the variance, a median goodness of fit across the WOIs was estimated as 0.28.

Discussion and Conclusion

Mechanisms that mediate dancing together in time were investigated in an experiment conducted in a live performance setting. Time-series analyses were applied to motion tracking data obtained during a with-music dance performance and a no-music version of the same work. One analysis sought evidence of scaling to explain differences in durations across the two conditions, and another sought evidence of lapsing. The analyses present a strong case for lapsing as the dominant mechanism that explains why the dancers concluded the piece slightly sooner (just 5%) when they performed the four-minute piece without music. Lapses accounted for nearly all of the difference (10.45 s out of 14 s), whereas scaling provided optimal fit when it was set to almost 1 (no scaling), median 0.997. A dancer's highly attuned internal clock is the likely mechanism that underpins felt time between dancers who are moving together in silence.

Importantly, there is a conceptual relationship between scaling and lapsing that the lapse analysis may have incorporated. Notice that in the lapse profile and the list of lapse frequencies that the largest number of lapses occur over very small time intervals, –0.05 and +0.05 seconds in particular (Figure 6). We argue that small consecutive lapses amount to miniature scaling episodes, or 'microscaling.' The analysis detects so many small lapses that they effectively could be grouped together as scaling episodes, such as in the vicinity of t = 12, 18, 35, 45, 105 s and so forth (see Figure 5). The scaling analysis did not detect these lapses because the window size was too long for that analysis. If the window size was made too short, though, we found that scaling would start being affected by lapses, increasing error. Further, the idea of an internal clock suggests that scaling should act in a constant, uniform, underlying fashion, and not as microscalings. We therefore conclude that these microscalings are kinds of lapses, rather than a special case of scaling.

For example, consider a case when a lapse occurred due to the dancer acting too late in response to waiting for a cue from another dancer. Once the dancers have realized the foible, all in a very short space of time, rather than an instantaneous correction, the dancer gradually increases his speed so as not to make the error too obvious. In this example, the dancer is deliberately microscaling to make a correction; in other words correcting an insertion with a deletion, but doing so deliberately and gradually.

The distribution of lapse durations is comparable to that found in finger tapping tasks (Chen, Ding, & Kelso, 2001; Chen, Repp, & Patel, 2002). Such tasks can be compared with the present work because of the requirement of tapping in synchrony with a metronome or without a metronome; that is, continuing tapping when the metronome stops, is analogous to the NM dance condition. In these studies the error (difference between target tap time and performed tap time) was found to be distributed in a $1/f^{\alpha}$ distribution (where f should be viewed here as the frequency or count of the various lapse durations). This means that most of the timing errors in tap time are very small, and therefore very close to the actual metronome time, with less frequent occurrence of longer duration errors. The present research supports this $1/f^{\alpha}$ distribution because the majority of lapses are of a short (possible microscaling) duration, with relatively fewer lapses of durations greater than $|\pm 0.1|$ s (Figure 6). Further, much of the time no lapses were detected (see Figure 5).

The present findings concerning the dominance of lapsing are consistent with musical performance. As discussed in the introduction, little scaling is found in imagined music performance tasks (e.g., Langheim et al., 2002; Repp, 1999). However, serial ordering can be a problem (Palmer & Pfordresher, 2003). The present results accord with these observations. While the present study did not identify periodicity or regularity in the short, microscaling lapses (assessed through a Fourier analysis), future work is recommended to investigate whether particular lapse lengths have a propensity to occur at certain locations—such as phrase boundaries—in the dance.

Further work will be required to scrutinize the complex nonlinear aspects of the way that scalings and lapses interact in memory for dance, if they do at all. The approach we have described here deals with the problem by applying two separate analyses, scaling and lapsing. The approach has applications to other similar problems where there is a time-locked condition, produced by the presence of music, and a no music condition, where the musical material may be audiated or imaged from memory.

As a corollary to the nexus between the underlying processes, Fu et al. (2008) describes a 'dynamic time warping with uniform scaling' approach to adjusting one time series to optimally match another: that is, their approach modeled both dynamic time warping (in the present study manifested as the detection of performance lapses) and uniform time scaling (here, detection of performance-time-scaling). This is an important innovation in finding optimal solutions to data matching problems. However, we found it useful to treat the two processes as separate because they are indicative of meaningfully distinct mechanisms from a psychological perspective (memory errors versus a miscalibrated internal clock).

The analytic technique provides a first step towards automatic detection of lapsing and scaling in dance movement and cognition using time-domain analytic techniques. We deliberately avoided the established, frequency-domain based technique of dynamic time warping because we wanted to tease out the lapse specific aspects between two conditions, something which traditional dynamic time warping does not intrinsically guarantee. It should be noted, though, that our method consists of several parameters that were set through pragmatic choice and experimentation, such as the window sizes (WOI and subwindows), sampling rate, the need for overlapping windows (which, while covering the entire series, may also doubly detect lapses), and the threshold of significance for a lapse, scaling, and goodness of fit. Further work will be required to refine the approach and principles according to which the various parameters are to be set, and to improve the efficiency of the algorithm. However, we are not aware of any other attempts to implement such detection in the time-domain, and we emphasize the advantages of separating lapses and scaling in the context of investigating underlying psychological mechanisms. Clearer identification of lapse and/or scaling mechanisms will be easier in the simplified setting of a single dancer whose motion is tracked in WM and NM conditions.

The focus here has been on the effect of the presence and absence of musical cues on motor recall. The relatively simple experimental design lends itself to further detailed analysis of the underlying code in memory. For example, in the NM condition, dancers could reproduce the movements without imaging the music, with the accurate reproduction of timing based on motor memory. One way to investigate the role of motor memory versus auditory imagery would be to present dancers with a novel motor or auditory motif that they would be asked to recall at the conclusion of the dance piece. If motor memory is involved, then rehearsing the novel motor motif should interfere with recall of the dance, whereas if auditory imagery is involved then rehearsal of the auditory motif should interfere with recall of the dance.

Dance is a rich source of material for investigation of production and perception of expressive, non-verbal, kinesthetic and visual cues and the interplay of implicit and explicit knowledge (Stevens et al., 2003; Stevens & McKechnie, 2005). The method described here provides an automated way of detecting lapses and scalings. Possibilities in the future application of this method include analysis of: repeat performances of the no-music and with-music conditions (data that are available from the project connected with the present paper), a highly rehearsed dance piece, and the timing of a solo dancer. Point-light or animations generated from the motion capture data may be used to test in controlled perceptual experiments specific predictions concerning the interplay of music and movement, and an interference paradigm introduced to investigate the effects of visual, spatial, motor, and auditory codes on memory for timing and movement in performer and in observer.

Author Note

This research was supported by the Australian Research Council through its Linkage Project and Infrastructure grant schemes (Grant Numbers: LP0211991, LP0562687, LE0347784, LE0668448), MARCS Auditory Laboratories at the University of Western Sydney, The University of New South Wales via its Strategic Investment in Research Scheme, and industry partners The Australia Council for the Arts Dance Board, The Australian Dance Council (Ausdance), and QL2 Centre for Youth Dance (formerly the Australian Choreographic Centre). Our thanks to the team at QL2—Mark Gordon, Ruth Osborne, Gary Barnes, Quantum Leap Choreographic Youth Ensemble, Emma Batchelor, James Batchelor, Rebecca Frasca, Sam Maxted, research colleagues Kim Vincs, Garth Paine, research assistants Clare Howell, Eva Walker, Tim Byron, Tajana Opacic, Kirk Olsen, Julien Tardieu, the editors, and three anonymous reviewers. Further information: http://marcs.uws.edu.au.

Correspondence concerning this article should be addressed to Catherine Stevens, School of Psychology and MARCS Auditory Laboratories, University of Western Sydney—Bankstown, Locked Bag 1797, South Penrith DC NSW 1797 Australia. E-MAIL: kj.stevens@uws.edu.au

References

BRANNON, E. M., LIBERTUS, M. E., MECK, W. H., & WOLDORFF, M. G. (2008). Electrophysiological measures of time processing in infant and adult brains: Weber's Law holds. *Journal of Cognitive Neuroscience*, *20,* 193-203.

CALVO-MERINO, B., GLASER, D. E., GRÈZES, J., PASSINGHAM, R. W., & HAGGARD, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. *Cerebral Cortex, 15,* 1243-1249.

CHEN, Y., DING, M., & KELSO, J. A. S. (2001). Origins of timing errors in human sensorimotor coordination. *Journal of Motor Behavior, 33,* 3-8.

CHEN, Y., REPP, B. H., & PATEL, A. D. (2002). Spectral decomposition of variability in synchronization and continuation tapping: Comparisons between auditory and visual pacing and feedback conditions. *Human Movement Science*, *21,* 515-532.

CUNNINGHAM, M. (1968). *Changes: Notes on choreography.* New York: Something Else Press, Inc.

DIXON, S., & WIDMER, G. (2005). MATCH: A music alignment tool chest. Online *Proceedings of the 6th International Conference on Music Information Retrieval* (ISMIR), 492-497. London: International Society for Music Information Retrieval. http://ismir2005.ismir.net/proceedings/index.html

FOSTER, R. (1976). *Knowing in my bones*. London: Adam & Charles Black.

FU, A. W.-C., LAU, L. Y. H., & WONG, R. C.-W. (2008). Scaling and time warping in time series querying. *The VLDB Journal, 17,* 899-921.

GARDNER, H. (1993). *Frames of mind: The theory of multiple intelligences* (2nd ed.). London: Harper Collins.

GEISSLER, H. G. (2000). Processing of time—processing time: Temporal invariants and oscillatory mechanisms in perception and memory. *Zeitschrift für Psychologie, 208,* 129-168.

GROVE, R., STEVENS, C., & MCKECHNIE, S. (Eds.). (2005). *Thinking in four dimensions: Creativity and cognition in contemporary dance.* Carlton: Melbourne University Press.

HALPERN, A. R. (2001). Cerebral substrates of musical imagery. *Annals of the New York Academy of Sciences, 930,* 179-192.

HANNA, J. L. (1979). *To dance is human: A theory of nonverbal communication.* Chicago: The University of Chicago Press.

HETLAND, M. L. (2004). A survey of recent methods for efficient retrieval of similar time sequences. In M. Last, A. Kandel, & H. Bunke (Eds.), *Data mining in time series databases* (pp. 23-42). London: World Scientific.

LANGER, S. K. (1953). *Feeling and form*. London: Routledge & Kegan Paul Limited.

LANGHEIM, F. J. P., CALLICOTT, J. H., MATTAY, V. S., DUYN, J. H., & WEINBERGER, D. R. (2002). Cortical systems associated with covert music rehearsal. *NeuroImage, 16,* 901-908.

LAST, M., KANDEL, A., & BUNKE, H. (Eds.). (2004). *Data mining in time series databases.* London: World Scientific.

LIMÓN, J. (1955). Composing a dance. *The Juilliard Review*, *II,* 17-25.

LUCE, P. A., & PISONI, D. B. (1998). Recognizing spoken words: The neighborhood activation model. *Ear and Hearing, 19,* 1-36.

NAGELKERKE, N. J. D. (1991). A note on a general definition of the coefficient of determination. *Biometrika, 78,* 691-692.

O'SHAUGHNESSY, D. (2008). Invited paper: Automatic speech recognition: History, methods and challenges. *Pattern Recognition, 41,* 2965-2979.

PALMER, C., & PFORDRESHER, P. (2003). Incremental planning in sequence production. *Psychologcal Review, 110,* 683-712.

REPP, B. H. (1999). Control of expressive and metronomic timing in pianists. *Journal of Motor Behavior, 31,* 145-164.

SACHS, C. (1937). *World history of the dance.* New York: W.W. Norton & Company.

SCHUBERT, E. (2002). Correlational analysis of continuous emotional response to music: Correcting for the effects of serial correlation. *Musicae Scientiae, Special Issue,* 213-236.

STEVENS, C., MALLOCH, S., MCKECHNIE, S., & STEVEN, N. (2003). Choreographic cognition: The time-course and phenomenology of creating a dance. *Pragmatics and Cognition, 11,* 299-329.

STEVENS, C., & MCKECHNIE, S. (2005). Thinking in action: Thought made visible in contemporary dance. *Cognitive Processing, 6,* 243-252.

VAUGHAN, D. (1990). Merce Cunningham. In *Cage, Cunningham, Johns: Dancers on a plane* (pp. 81-87). London: Thames & Hudson.

APPENDIX. Description of the Dance and Distribution of Activity Across Three Dancers.

Time*	Event	Motion-tracked male dancer	Male dancer (red shirt)	Female dancer (purple dress)	All dancers
14:55:31:000	First move	x			
14:55:34:500	First long stretch—quality shift	x			
14:55:38:500	First vertical stretch—axis shift	x			
14:55:41:500	Accent leads to even slower stretch (builds on previous quality)	x			
14:55:45:500	Long back arch—quality shift and shape shift	x			
14:55:46:500	Second dancer joins in		x		
14:55:49:000	Accented vertical movement	x			
14:55:50:000	Second dancer breaks unison—spatial counterpoint	x	x		
14:55:55:000	Third dancer joins			x	
14:55:58:500	Third dance qualitative change & others are stopped (becomes solo)			x	
14:56:04:000	Three stand together—look about to start something in unison				x
14:55:05:500	Two men move off suddenly—disrupts expectation of unison	x	x		
14:56:22:500	Woman joins to make trio, but with different movement (counterpoint)			x	
14:56:25:500	Circular jumps, first men, then woman				x
14:56:26:000	Woman begins a new 'solo'			x	
14:56:34:000	Men begin again—with speed	x	x		
14:56:36:500	Woman change of quality—sustained back arch with curving hand detail			x	
14:56:38:000	Woman begins high energy 'big leg' movements			x	
14:56:44:500	Men join in	x	x		
14:56:45:500	All jump				x
14:56:46:000	One man does tour on spot		x		
14:56:49:500	All do bigger jump				x
14:56:52:000	Trio converge and woman begins vertical arm movement				x
14:56:54:500	Duo section begins		x	x	
14:56:58:000	Unison resumes with circular arm movement				x
14:57:21:000	Dancers form diagonal line—anticipate new section				x
14:57:45:000	Slow cross arm movement—change in quality & dynamic				x
14:57:49:000	One man breaks from unison	x			
14:58:04:000	Duo does circular move on knee—increasing virtuosity		x	x	
14:58:06:500	Upstage dancer revealed				x
14:58:15:000	Couple 'hug,' upstage solo dancer increases range and 'reach' of movement				x
14:58:28:500	Couple stand up		x	x	
14:58:32:000	Couple separate—looks as though woman will walk towards the other dancer				x
14:58:35:500	Woman touches man's arm—initiates duet	x		x	
14:58:46:000	Dramatic 'swing' move in duet	x		x	
14:58:55:000	Duet still, solo man changes quality—slow swaying arm movements				x

(*Continued*)

APPENDIX. (**Continued**)

14:58:57:000	Solo man rises from floor and begins vertical arm movement		x		
14:59:04:000	Couple begin to move—still counterpoint to solo man	x		x	
14:59:14:000	Solo man rolls towards couple—anticipation that he will interact with them in some way		x		
14:59:17:000	Solo man joins others in a line & unison commences				x
14:59:25:500	Possibly recognize initial movement phrase of mocap man—anticipate end of dance				x
14:59:35:500	Mocap man stays still while others continue—counterpoint	x			
14:59:42:000	Woman detaches from group—anticipation that she will interact in a new way with red shirt			x	
14:59:51:000	Woman still—others have already stopped moving—signals end of dance			x	

*Performance commences at clock time 2.55 pm (14:55:31:000). Time shown is Hours:Minutes:Seconds:Milliseconds.