Nesting of asymmetric functions in skilled bimanual action: Dynamics of hammering behavior of bead craftsmen

Tetsushi Nonaka a,*, Blandine Bril b

a Research Institute of Health and Welfare, Kibi International University, 8 Iga-machi, Takahashi, Okayama 716-8508, Japan
b Groupe de Recherche Apprentissage et Contexte, École des Hautes Études en Sciences Sociales, 54 Bd Raspail, 75006 Paris, France

A R T I C L E   I N F O

Article history:
Available online 4 May 2011

PsycINFO classification:
2330

Keywords:
Affordances
Tool-use
Expertise
Bimanual coordination

A B S T R A C T

In human manual activities, the two hands are often engaged in differentiated roles while cooperating with each other to produce an integrated outcome. Using recurrence methods, we studied the asymmetric bimanual action involved in stone bead production by craftsmen of different skill levels, and examined (a) how the control of unilateral movement is embedded in that of a bimanual system, and (b) how the behavior of a bimanual system is embedded in the context of the function performed in the world. Evidence was found that the movements of the two hands of experts were functionally linked, reflecting the roles assumed by each hand. We further found that only the dynamics of bimanual coordination of experts differentiated the functional requirements of different sub-goals. These results suggest that expertise in this skilled bimanual action lies in the nesting of functionally specific adjustments at different levels of a control hierarchy.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

The repertoire of asymmetric manual activity in our everyday lives is incredibly large. In a vast majority of human manual acts of everyday life, the two hands are engaged in qualitatively differentiated roles, while cooperating with each other to achieve an overall goal. From most common everyday activities such as unlocking and opening a door, using scissors, folding a letter or opening a can, to skilled activities such as playing the cello or serving in tennis, in all cases the functions achieved by the two hands are clearly differentiated yet coordinated at the same time.

* Corresponding author. Tel.: +81 (0)86 66 22 37 09.
E-mail addresses: tetsushi.nonaka@gmail.com (T. Nonaka), blandine.bril@ehess.fr (B. Bril).

0167-9457/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.humov.2010.08.013
The most widely studied bimanual coordination phenomena involve symmetric rhythmic movement of the two upper limbs, arising from Haken, Kelso, and Bunz’s (1985) model of bimanual limb control (see Beek, Peper, & Daffertshofer, 2002; Newell, Liu, & Mayer-Kress, 2008, for reviews). The main variable taken into account in the study of the coordination of human rhythmic movements is the relative phase (Bingham, Zaal, Shull, & Collins, 2001), the relative position of two oscillating limbs within an oscillatory cycle. Analyses have revealed that such movements interact to produce characteristic stable modes of coordination, with synchronous movement being the most stable (e.g., Kelso, 1995). While it is undeniable that studies on the intrinsic dynamics of symmetric bimanual coordination are informative, the attention paid to them seems to have resulted in a shift away from skills involving asymmetric bimanual coordination more commonly found in our everyday lives (Guiard, 1987).

Recently, interesting theoretical approaches have come to the fore addressing the phenomenon of asymmetrical yet complementary bimanual coordination. Sainburg and colleagues (Sainburg, 2002; Sainburg & Duff, 2006; Sainburg & Eckhardt, 2005; Sainburg & Schaefer, 2004) have proposed the dynamic dominance hypothesis, which states that each hand is specialized for distinct but complementary functions: the dominant hand for controlling hand trajectory and the nondominant hand for controlling stable hand posture. In this view, the nondominant hand is not viewed as a naïve, unpracticed analog of the dominant hand but as a complementary component of a bimanual system (Sainburg & Duff, 2006). Previous studies have provided substantial evidence that each hand is specialized for distinct functions (e.g., Sainburg, 2002; Sainburg & Schaefer, 2004). Yet, the problem of how such asymmetric bimanual activities are organized into the collective behavior of a bimanual system still remains largely unexplored.

Domkin, Laczko, Djupsjobacka, Jaric, and Latash (2005), and Domkin, Laczko, Jaric, Johansson, and Latash (2002) applied the uncontrolled manifold (UCM) approach to asymmetric bimanual movement coordination. The UCM method allows one to determine whether and how variability in elemental variables (e.g., joint angles) in a multi-element system (e.g., an arm) is exploited to control a performance variable (e.g., the trajectory of the endpoint in the external space). The UCM is defined as the set of all elemental variables that leaves the performance variable invariant (Scholz, Schöner, & Latash, 2000). According to the UCM hypothesis, if the performance variable is the controlled variable, a higher proportion of the variance in elemental variables in the UCM is expected compared to the uncompensated variance that affects the performance variable (Latash, Scholz, & Schöner, 2002; Scholz & Schöner, 1999; Scholz et al., 2000). In Domkin et al.’s (2002, 2005) studies, participants were instructed to match the tip of a pointer, held in one hand, with the tip of a target held in the other hand. Domkin et al. (2002, 2005) suspected two kinds of synergies for bimanual pointing. First, the joints of one arm may be compensated in such a way to stabilize trajectories of the endpoint of each arm (unimanual hypothesis). Second, all involved joints of the two arms may be compensated in such a way to stabilize a time profile of the distance between the tip of the pointer and the target (bimanual hypothesis). Analysis of the experimental data supported both hypotheses. However, when the ratios between the amounts of compensated and uncompensated variance were compared, this index for the bimanual hypothesis was significantly larger than for unimanual hypotheses (Domkin et al., 2002, 2005). This result confirmed that a bimanual pointing was not simply a superposition of two unimanual movements of the target and of the pointer but was functionally nested (cf., Reed, 1988), in which each unimanual movement was regulated with respect to the overall function of matching the target and pointer, involving a bimanual synergy (Domkin et al., 2002, 2005; Latash, 2008).

The UCM method of analysis requires elemental variables be known in advance. In many naturalistic situations, however, what contributes to the overall behavior of a system is unknown. Even in cases where elemental variables are known and measured, they are often in incommensurable units or exhibit nonlinear interactions in producing a performance variable of the system, which makes it difficult to build a formal linear model using a Jacobian of the system to estimate its UCM (Latash, 2008). While the UCM methods have an advantage in making it possible to formulate exactly that there is a synergy within such-and-such space of elemental variables with respect to such-and-such performance variable, its application is limited to controlled tasks in relatively simplified situations.

Features of a dynamical system whose elemental variables are unknown may be probed by nonlinear time series analyses developed recently (Riley, Balasubramaniam, & Turvey, 1999; Riley & Turvey,
In a mathematical theorem termed the embedding theorem (Takens, 1981), it is shown that for a nonlinear dynamical system, one needs to measure only one variable to gain information about the underlying dynamics. In other words, while the actual dimension of the system is set by the number of state variables, we may only need to measure one of those variables to learn interesting features of the system’s underlying dynamics (Webber & Zbilut, 2005). Using the measured signal and time-delayed copies of the signal, one can reconstruct the phase space of the dynamical system (for details, see Abarbanel, 1996). Phase space reconstruction forms the basis of a variety of nonlinear time series analyses, including recurrence quantification analysis (RQA).

As in the UCM method, RQA considers variability as a phenomenon informative about the nature of biological processes, and extracts the invariant temporal structures from varying states over time (cf., Riley & Turvey, 2002). The first step in RQA is to determine how frequently the movement trajectory revisits locations in reconstructed phase space (i.e., how frequently states recur). This is captured by the RQA variable $\%REC$. The patterns of recurrence can then be used to quantify the dynamical structure of the time series as characterized by other variables including $\%DET$ which reflects the deterministic (predictable) structure of the dynamics, and $L_{\text{max}}$ that quantifies the dynamic’s robustness to perturbation (Cluff, Riley, & Balasubramaniam, 2009; Riley, Baker, Schmit, & Weaver, 2005; Riley et al., 1999).

This technique is also used to quantify shared activity between two time series, namely, cross recurrence quantification analysis (CRQA) (Shockley, Baker, Richardson, & Fowler, 2007; Shockley, Butwill, Zbilut, & Webber, 2002; Shockley et al., 2003; Zbilut, Giuliani, & Webber, 1998). CRQA is known to be highly sensitive to the subtle space–time correlations that can occur between two motion trajectories (Shockley et al., 2002). CRQA quantifies, among others, the degree of shared activity ($\%CREC$, the percentage of states in the two movement trajectories that are shared in the reconstructed phase space), the degree of determinism in the dynamics of shared activity ($\%CDET$, the percentage of shared states that have common trajectories) and the degree of dynamical stability of shared patterns ($CL_{\text{max}}$, the maximum number of consecutive states that are shared over time and form a sequence of shared states) between two time series signals (Shockley et al., 2002, 2003).

CRQA has been applied to the phenomenon of interlimb rhythmic coordination, the results of which have also been interpreted in the framework of the HKB model (Pellecchia, Shockley, & Turvey, 2005; Richardson, Lopresti-Goodman, Mancini, Kay, & Schmidt, 2008; Richardson, Schmidt, & Kay, 2007; Shockley & Turvey, 2005). For instance, Pellecchia et al. (2005) conducted CRQA on the time series measuring displacement in the sagittal plane from markers attached to two hand-held pendulums oscillated in in-phase coordination. They suggested that $\%CREC$ provides an index of the magnitude of noise in the system (in the sense of the proportion of shared points to other points in reconstructed phase space) and that $CL_{\text{max}}$ provides an index of the system’s sensitivity to perturbations (i.e., the strength of the attractor against perturbations) (Pellecchia et al., 2005). This was subsequently validated by Richardson et al. (2007), who experimentally manipulated noise magnitude and attractor strength independently. The application of recurrence methods to the well-defined phenomena of symmetric bimanual coordination is highly informative. However, by taking full advantage of their features, it should also be possible to apply the recurrence methods to the quantification of dynamical characteristics of asymmetric, yet functionally coupled activities in natural contexts (e.g., Shockley et al., 2003).

Recurrence methods, unlike the UCM method, cannot provide an exact formulation of a synergy, since the collective features of a system are explored without identifying the system’s state variables. But recurrence methods have advantages in requiring fewer assumptions than the UCM methods, which allows application to a wide range of real-life behavior to probe the features of underlying dynamics.

The current study, taking advantages of the recurrence methods, investigated an everyday specialized task where each hand has a singular role—stone bead production—which is performed in a small town in Gujarat (India). The aim of this study was to investigate (a) how the control of unilateral movement is embedded in that of a bimanual system, and (b) how the behavior of a bimanual system is embedded in the context of the function performed in the world. We conducted a field experiment of professional stone bead craftsmen to capture the skilled actions in the setting where they actually
took place. The goal of the task was to shape an ellipsoidal bead using a specific technique, in which, with one hand holding the hammer and the other holding a stone, the different streams of activities of the two hands are nested into a unified act that leads to the shaping of a stone. It is a good example of real life tool-use that necessitates fully distinct activities of both hands, one hand performing striking movements, while the other hand positions the object to be hit (cf., *Sainburg & Eckhardt, 2005*). The hammering frequency is very high (3.5 Hz on average for expert craftsmen) and the orientation and position of the object to be hit is continuously changed, which makes this bimanual task highly demanding. The fact that it normally takes seven to ten years for an apprentice to become a professional craftsman in high quality workshops illustrates the difficulty of this task (*Roux, Bril, & Dietrich, 1995*).

### 1.1. Stone bead production in India

The current study is one of the series of experimental studies on dexterity of stone beads craftsmen in India (*Biryukova & Bril, 2008; Bril, Roux, & Dietrich, 2000, 2005; Roux, 2000; Roux et al., 1995*). The shaping of hard stone beads depends on the specific properties of the raw material used (*Bril et al., 2000, 2005; Pelegrin, 1993; Roux et al., 1995; Roux & Pelegrin, 1989*). Carnelian, a type of quartz typically used in stone bead production, has the natural property of conchoidal fracture, which allows craftsmen to fracture the stone in a controlled manner (*Bril et al., 2005; Nonaka, Bril, & Rein, 2010*). With one hand, which we call the *postural hand*, the craftsman holds a piece of stone between his fingers and places the edge of the stone against the pointed tip of an iron bar. With the other hand, which we call the *hammering hand*, the craftsman strikes the piece with the hammer so that a stone flake is fractured from the point of contact with the iron bar (*Fig. 1*). This technique, which has been referred to as indirect percussion by counter-blows (*Pelegrin, 1993*), is brought into play to produce flakes of different profiles in such a way to shape the stone into a specific form (*Bril et al., 2005*).

The production of ellipsoidal beads is a two-stage process (*Fig. 2*). First, a piece of raw material is shaped into a parallelepiped-shaped roughout with four crests (step 1). Then the craftsmen detach the four crests of the roughout to shape an ellipsoidal preform (step 2). In the current study, we focus on step 2, shaping of an ellipsoidal preform from a parallelepiped-shaped roughout (*Fig. 2*). This process is further broken down into the following three sub-goals: calibration, end preparation, and fluting (*Bril et al., 2000, 2005; Roux et al., 1995*). Calibration consists of the detachment of a series of thin and short flakes to standardize the crests for successful fluting. End preparation is the preparation of the striking surface used for crest fluting. Fluting is the detachment of an elongated flake running along the crest at once. In the current experiment, two phases in the process of shaping an ellipsoidal preform—calibration and fluting—are studied (*Fig. 3*). The functional requirements vary according to the sub-goal. Calibration consists of a series of light hammer tapping and constant repositioning of the roughout to smooth its crests little by little (*Fig. 7A*), while fluting consists of preparatory...

---

**Fig. 1.** Typical posture and movement of craftsmen during stone bead production through indirect percussion by rebound. The motion capture sensors were attached to the dorsal surface of the two hands.
oscillation of the hammer followed by a forceful strike to remove, at once, an elongated, thick flake running along the crest (Fig. 7B). Fluting is said to be the most demanding phase in the production of an ellipsoidal bead (Roux et al., 1995), which irreversibly determines the overall shape of a bead through a single strike.

Previous studies on the movement involved in stone bead production have focused exclusively on the hammering hand during fluting (Biryukova & Bril, 2008; Bril et al., 2000, 2005; Roux et al., 1995). Roux and colleagues (Bril et al., 2005; Roux et al., 1995) compared the movement of the hammering hand during fluting of the craftsmen from two kinds of workshops, high quality (HQ) and low quality (LQ) (Bril et al., 2005; Roux et al., 1995). They introduced a novel raw material, glass, which has the same natural property of conchoidal fracture but more fragile and homogeneous than carnelian stone that is normally used. It was found that the hammering movements of both HQ and LQ differentiated glass from stone, in which the acceleration of the hammer was always much smaller for glass compared to stone (Bril et al., 2005; Roux et al., 1995). In terms of the quality of the end products, however, the difference across groups was amplified in the glass condition, in which the performance of LQ was greatly deteriorated compared to the carnelian condition, and only HQ craftsmen were able to take advantage of the properties of the glass in such a way to shape ellipsoidal beads (Fig. 4, see Bril et al., 2005 for details). Furthermore, in both material conditions, the proportion of strikes that failed in detaching flakes during fluting was twice as high in LQ as in HQ (Bril et al., 2005). These results raised the question where such difference in performance across groups came from.

Fig. 2. The two steps of the fabrication of an ellipsoidal bead, (1) from raw material to a parallelepiped-shaped roughout, and (2) from a roughout to an ellipsoidal preform. Only the second step is considered in the present experiment.

Fig. 3. Three sub-goals of an ellipsoidal bead production: calibration, end preparation, and fluting. Black arrows represent the direction of the hammer blows. Only calibration and fluting were considered in the present study.

Fig. 4. Examples of glass preforms produced by an HQ and an LQ craftsman.
In the subsequent study, Biryukova and Bril (2008) investigated the characteristics of the movement of the hammering arm of HQ craftsmen. They reported that the number of joints involved in fluting movement of the hammering arm and their combinations increased as a function of skill level. Furthermore, the largest variability of the hammerhead direction during a strike was found in the most skilful expert. Given these results, Biryukova and Bril (2008) speculated that the variability of hammering direction was the expression of the functional link between two hands of the expert in which the movement of one compensates that of the other. Although they did not measure the movement of the postural hand, Biryukova and Bril (2008) suggested the possibility that “although the two arms have quite different functions, they become, with increasing levels of motor skill, more and more functionally linked, thus reducing the numbers of parameters to be controlled (p. 201).”

Extending earlier findings of the control of the hammering hand in the skill of stone bead production, our research was designed to explore the issues of how the control of unilateral movement is embedded in that of a bimanual system, and how the behavior of a bimanual system is embedded in the context of the function performed in the world. Our hypotheses were threefold. First, as Biryukova and Bril (2008) suggested, we expected to see more stable and more deterministic coupling between the hands of experts than non-experts, which would be reflected in CRQA measures. Second, we hypothesized that both bimanual coordination and unilateral movement would specify the functional demands of the task. Specifically, we expected to see the increase of proportion of recurrence (indexed by %REC and %CREC) and attractor strength (indexed by CLmax and Lmax) in the dynamics of movement during fluting, in which subtle disruption of the movement may lead to the failure of the entire task (Roux et al., 1995). We also expected that the amplitude of hammering movement would be scaled to the magnitude of percussive force required in different sub-goals and raw material conditions. Third, replicating the previous results, the difference between HQ and LQ was expected to be amplified in the glass condition. We expected that the introduction of the novel material would disrupt the control of movement of LQ, while that of HQ would be stable regardless of the material used. We then further explored the question what underlies the amplified difference in performance in the glass condition between HQ and LQ.

2. Method

2.1. Participants

In Khambat, the workshops which produce superior quality beads and the workshops which produce lower quality beads are clearly distinguished, and the craftsmen are given different socio-economic status according to the workshops they belong to (Roux et al., 1995). Participants were recruited from these two classes of workshops. HQ consisted of six expert craftsmen from the higher quality workshops. LQ consisted of six craftsmen from the lower quality workshops. Craftsmen from both groups manufacture beads for their living. In total, 12 professional stone bead craftsmen took part in the experiment.

All the craftsmen in the study volunteered, and for their participation they were paid the highest rate for one day’s work. They gave their verbal agreement to participate in the study to the owner of the workshop, who hosted the experiment. No written consent was demanded because this does not meet local tradition in which a written agreement would have been considered as a lack of trust. For more details, see Bril et al. (2000).

2.2. Apparatus

Following Roux et al. (1995), in addition to carnelian stone typically used in bead production, glass was included as raw material. 6 × 2.5 × 2.5 cm parallelepiped-shaped pieces of glass and pieces of carnelian stone with approximately the same size were used as the roughouts (Fig. 5). The hammer used in the experiment had the following properties: weight of hammerhead = 22 g, handle length = 35 cm, handle weight = 7 g.
The entire session was recorded by two video cameras positioned in front of the craftsman, with an angle of approximately 120°. A Spatial Tracking System (STS-Polhemus) was used to record the movements of the two hands. This system uses an electromagnetic field to determine the three-dimensional positions and orientations of the sensors relative to the stationary system. The static accuracy of the STS system was 0.08 cm RMS for the sensor positions and 0.15° RMS for the sensor orientations. Calibration measurements showed that the system was accurate within 0.7 m of the origin of the stationary system. The two sensors of the STS were firmly attached with adhesive tape to the dorsal surface of the two hands of each participant (Fig. 1). Movement data (displacement in centimeters) were recorded at 60 Hz. Both sensors were within a 0.7-m sphere of the stationary system to ensure acceptable accuracy of the STS. The craftsmen reported that the sensors were not a hindrance.

Biryukova and Bril (2008) placed an additional sensor on the handle of the hammer ($M_{\text{handle}}$ in Fig. 6) to test whether the hammer moved relative to the hand sensor ($M_{\text{hand}}$ in Fig. 6), and confirmed that relative positions and orientations of the sensor on the hand to the one on the handle of the hammer varied very little during test trials. Accordingly, they reconstructed the working point (WP in

---

**Fig. 5.** Two kinds of roughout made of different raw materials used in the experiment (glass and carnelian stone).

**Fig. 6.** The assessment of the rigidity of the ‘hand + hammer’ system in Biryukova and Bril (2008). $\vec{d}_{\text{hand}}$ and $\vec{d}_{\text{handle}}$ are the positions of the sensor located on the hand and on the handle of the hammer in the stationary system XYZ measured by the STS. $\vec{d} = \vec{d}_{\text{hand}} - \vec{d}_{\text{handle}}$ is the vector used for validation of rigid body assumption for the system ‘hand + hammer’.
Following Biryukova and Bril (2008), we assumed that the movement of the hand sensor reflects that of the working point. However, it should be noted that the functional task of hammering is defined at the interface between the working point and the surface of a roughout.

2.3. Procedure

The craftsmen were in a situation as close as possible to their everyday activity. Participants sat on a rug in their preferred sitting posture. All of them used the posture illustrated in Fig. 1. The task consisted of shaping a 6 × 2.5 × 2.5 cm parallelepiped-shaped roughout into an ellipsoidal preform (Fig. 2). In the current experiment, two phases in the process of shaping an ellipsoidal preform—calibration and fluting—are studied (Fig. 3). A session consisted of producing a series of five samples of beads of each of the two raw materials. The craftsmen were instructed to produce an ellipsoidal bead and to take their time to manufacture a bead of high quality. The instructions were given in Gudjerati, the language spoken in that region of India.

2.4. Data reduction

By labeling the video recording with Actogram software (Octares Editions, Toulouse), the first 30-s sequences of calibration (standardization of crests to prepare for fluting) and fluting (detachment of long crests) were extracted from each trial. The reasons for selecting the first 30 s of a performance for the analyses were that the beginning of calibration and that of fluting could be identified without ambiguity, and that the entire process of shaping preforms (i.e., calibration, end preparation, and fluting) lasted only about two minutes and it was often not possible to extract a part longer than 30 s or to select other parts within the same trial. Sometimes, the duration of a sub-goal sequence was shorter than 30 s, and in such cases the trial was reported as missing. In total, 108 calibration and 113 fluting sequences contributed to the analysis. Videos were only used to select the parts of the data that were fit for analyses. All further analyses were done on the data from the markers of the STS system.

In both sub-goal sequences, the hammering hand was almost constantly oscillating. As hammering primarily consists of movement in the vertical direction, displacement of each hand in the vertical direction was selected for the analysis. To obtain a quantitative description of such periodic movement, first, the peaks of oscillations of the displacement of the hammering hand in vertical direction were detected using a slightly modified version of the open-source algorithm by Billauer (2007) (Fig. 7). Subsequently, amplitudes (peak-to-peak distances in three-dimensional space) and periods (time from one local minimum to the next) of each cycle oscillation were computed based on the detected peaks. Then within each 30-s sequence, mean amplitude ($M_{ab}$), standard deviation of amplitude ($SD_{ab}$), mean cycle period ($M_{ph}$) and standard deviation of cycle period ($SD_{ph}$) of the oscillation of the hammering hand were calculated to describe the characteristics of the hammering movement. The postural hand, in contrast, did not exhibit such clear periodicity in the movement, and we simply used the mean ($M_{zp}$) and standard deviations ($SD_{zp}$) of position in the vertical direction relative to the floor, and the mean ($M_{vp}$) and standard deviations ($SD_{vp}$) of resultant velocity at each frame (1/60 s) within each 30-s sequence as dependent measures.

During each fluting sequence, the actual detachment of the longitudinal crests does not occur more than eight times, because there are only four crests to be removed on each end of one parallelepiped roughout. As such, each fluting sequence usually consists of small preparatory movements and a few fluting movements with greater amplitude (Fig. 7B), whereas each 30-s calibration sequence involves a series of detachment of a number of tiny flakes (Fig. 7A).

In the previous experiment, the quality of ellipsoidal beads produced by HQ and LQ was compared through the filming of the beads from eight different angles and the computation of parameters indexing the overall shape, the symmetries along the longitudinal and transversal axis, and the contour of the bead in terms of regularity and smoothness (see Bril et al., 2000, 2005 for details). All these criteria clearly distinguished the products of the two groups of craftsmen, in which HQ craftsmen had systematically produced more spherical and symmetrical beads with smoother contour (Fig. 4). As five out of six HQ craftsmen and two out of six LQ craftsmen took part in both the previous and current
experiments, building on these previous results, the current study did not include the analysis of the beads but focused on the aspect of the bimanual behavior.

2.5. Recurrence quantification analysis

We performed CRQA to quantify the spatiotemporal dynamics of the bimanual movement coordination (Fig. 8), and also performed RQA to quantify those of the movement of each hand alone, using the programs KRQS and RQS (Webber, 2008), respectively.

CRQA was performed on the pairs of time series from each 30-s sequence using the following parameters. Following Shockley et al. (2003), the time series were converted into standard (z) scores to achieve a common scale without influencing the distribution of scores within each time series. The recurrence methods require the following input parameters: time delay, embedding dimensions, radius and line length. The time delay refers to the temporal offset between copies of the time series that are used as surrogate dimensions in reconstructed space. We computed the first minimum of the average mutual information function to determine the correlated activity (Abarbanel, 1996) using ten randomly sampled time series data of each hand from the experiments. Based on the above procedure, we selected the temporal separation of 18 data points (0.3 s).

The number of embedding dimensions is the number of dimensions required to unfold the dynamic structure of a system’s trajectory and is calculated using false nearest neighbors (FNN) analysis.
(Abarbanel, 1996; Richardson et al., 2007). The quantity $\%FNN$ is calculated as the percentage of neighboring points that diverge after the addition of another dimension and indicates the percentage of points in phase space that are near each other simply because one has used too few dimensions to observe the system’s dynamics. When enough dimensions have been used to reconstruct a system’s phase space such that proportion of false neighbors decreases to zero or asymptote at a non-zero level, adding further dimensions does not reveal any more about the system’s dynamics and, thus, the embedding dimension is equal to the number of dimensions at which this occurs (see Abarbanel, 1996; Mitra, Amazeen, & Turvey, 1998; Richardson et al., 2007). We computed $\%FNN$ of the sample time series data of each hand from the experiment using the time delay of 18 data points. The number of dimensions needed to capture the dynamics tended to be slightly greater for the postural hand (clustering about eight dimensions) than that of the hammering hand (about seven dimensions), and we selected the greater of the two, that is, eight dimensions, for CRQA.

Fig. 8. Sample cross-recurrence plots of (A) calibration, and (B) fluting, using the same data as presented in Fig. 7.
The radius defines a distance around a point of the first trajectory that, if another point of the second trajectory falls within, will be considered a recurrent point. It is necessary to select a radius large enough to capture recurrence above the resolution threshold of the measurement instruments. Furthermore, the radius needs to be small enough to avoid too many recurrent points. On the basis of these criteria, our selection was a radius of 34% of the mean distance separating points in reconstructed space. A line segment in this study was considered to be two consecutive recurrent points.

The above input parameters were used to compute \( \% \text{CREC} \) (the percentage of recurrent points in the reconstructed phase space), \( \% \text{CDET} \) (the percentage of recurrent points that have common trajectories), and \( L_{\text{max}} \) (the maximum number of consecutive states that are shared over time and form a sequence of recurrent points), which provide measures of noise magnitude, determinism, and attractor strength in the dynamics of bimanual coordination, respectively.

Based on the same procedure as described above, the following input parameters were selected for RQA of the movement of each hand: for the hammering hand, a delay of 15 samples (0.25 s), seven embedding dimensions with a recurrence inclusion radius of 18% of the mean distance separating points in reconstructed phase space; for the postural hand, a delay of 24 samples (0.4 s), eight embedding dimensions with a recurrence inclusion radius of 15% of mean distance separating points in reconstructed phase space. The number of consecutive recurrent points required to define a line segment was set at two for the analyses of both hands.

The above input parameters were used to compute \( \% \text{REC} \) (the percentage of recurrent points in reconstructed phase space), \( \% \text{DET} \) (the percentage of recurrent states that are part of a string of adjacent recurrent points) and \( L_{\text{max}} \) (the maximum number of consecutive states that form a string of recurrent points), which provide measures of repeatability of states, determinism, and stability in the dynamics of unilateral movement, respectively. The mathematical methods of CRQA and RQA have been described in detail elsewhere (Webber & Zbilut, 2005, 2007).

2.6. Statistical analysis

Dependent variables calculated for each 30-s sequence were used for statistical analyses. A linear mixed-model ANOVA with sub-goal, group and raw material as fixed-effects and participants as a random effect was conducted for each dependent variable. To account for the correlation between trials made by the same participant, a participant factor was included as an additional random-effect (Boyle & Willms, 2001). Bonferroni-corrected post hoc analysis was used for multiple comparisons. A simple linear regression analysis was also conducted to test the correlation between linear dependent measures. All the statistical tests were made using SPSS 16.0. The alpha value for a significant effect was set at .05 in all the statistical analyses.

3. Results

This section is divided into three parts: the results of the analyses of (1) bimanual coordination between the two hands, (2) the movement of the hammering hand, and (3) the movement of the postural hand.

3.1. Bimanual coordination

In the ANOVA on \( \% \text{CREC} \) obtained from CRQA on pairs of displacement signals from the two hands, the only significant effect was an interaction between sub-goal and group, \( F(1, 204) = 14.84, p < .001 \). A post hoc analysis indicated that only for HQ, the proportion of shared activity in the reconstructed phase space (\( \% \text{CREC} \)) was greater during fluting compared to calibration, \( p < .001 \) (Fig. 9A). Contrary to HQ, when LQ used glass, \( \% \text{CREC} \) tended to be higher when they were calibrating than when they were fluting.

An ANOVA on \( L_{\text{max}} \) found a main effect of sub-goal, \( F(1, 204) = 7.61, p < .01 \), as well as an interaction between sub-goal and group, \( F(1, 204) = 10.53, p < .01 \). A post hoc analysis indicated that only for
HQ, the dynamics of shared activity in reconstructed phase space was significantly less sensitive to perturbations (longer CL\textsubscript{max}) during fluting compared to calibration, \(p < .001\) (Fig. 9B).

\%CDET was greater for HQ than for LQ, \(F(1, 10) = 5.06, p < .05\), suggesting that the dynamics of shared activity were more deterministic (predictable) for HQ compared to LQ. An ANOVA on \%CDET also found a main effect of sub-goal, \(F(1, 204) = 17.61, p < .001\), as well as a significant interaction between sub-goal and raw material, \(F(1, 204) = 3.93, p = .049\). A post hoc analysis indicated that only when glass was used, \%CDET was significantly lower during calibration compared to fluting, \(p < .001\). Particularly for LQ in the glass condition, the dynamics of bimanual activity during calibration was considerably less deterministic (Fig. 9C).

3.2. Hammering hand

3.2.1. Amplitude

In the ANOVA on \(M_{ah}\), significant main effects were obtained for sub-goal, \(F(1, 203) = 9.08, p < .01\), and raw material, \(F(1, 203) = 103.45, p < .001\). An interaction between these two factors, \(F(1, 203) = 8.40, p < .01\), and the three-way interaction, \(F(1, 203) = 4.65, p < .05\) were also significant. A post hoc analysis revealed that craftsmen from both groups oscillated their hammering hands with significantly greater amplitude when stone was used than when glass was used for both sub-goals, \(p < .001\) (Fig. 10A). The post hoc analysis further revealed that only when glass was used, LQ moved their hand with significantly greater amplitude when they were fluting than when they were calibrating, \(p < .001\).
The ANOVA on $SD_{ah}$ found significant main effects of sub-goal, $F(1, 203) = 104.22, p < .001$, and raw material, $F(1, 204) = 112.29, p < .001$, as well as a significant interaction between these two factors, $F(1, 203) = 4.55, p < .05$, and in the three-way interaction, $F(1, 203) = 13.55, p < .001$. Post-hoc analysis revealed that both HQ and LQ moved their hammering hands with greater variability in amplitudes when they were fluting than when they were calibrating, $p < .01$. It was also found that both HQ and LQ moved their hammering hands with greater variability in amplitude when stone was used than when glass was used, $p < .01$. During calibration using glass, LQ moved their hands with smaller variability in amplitude than HQ, $p < .05$ (Fig. 10B).

### 3.2.2. Period

In the ANOVA on $M_{ph}$, sub-goal was significant, $F(1, 203) = 25.01, p < .001$. Sub-goal and raw material both exhibited interactions with group: sub-goal by group, $F(1, 203) = 32.84, p < .001$, and raw material by group, $F(1, 204) = 4.72, p < .05$. The three-way interaction was also significant, $F(1, 203) = 5.50, p < .05$. A post hoc analysis found that LQ moved their hammering hands with higher frequency (shorter mean period) during calibration compared to fluting, $p < .001$. During calibration using glass, LQ moved their hammering hands with higher frequency than HQ, $p < .01$. During calibration, HQ, on average, moved their hammering hands with lower frequency when glass was used than when stone was used, $p < .01$ (Fig. 10C).

In the ANOVA on $SD_{ph}$, the effect of sub-goal was significant, $F(1, 203) = 66.65, p < .001$. Sub-goal and raw material both exhibited significant interactions with group: sub-goal by group,
Post-hoc analysis revealed that both HQ and LQ moved their hammering hands with greater variability in frequency during fluting compared to calibration in both raw material conditions, \( p < .001 \), replicating the result of amplitude. During calibration, the frequency of hammering movement of LQ was less variable than HQ, \( p < .05 \). When glass was used, the frequency of hammering movement of LQ was also less variable than HQ, \( p < .05 \). Only HQ moved their hammering hands with greater variability in frequency when glass was used than when stone was used, \( p < .01 \) (Fig. 10D).

### 3.2.3. RQA

In the ANOVA on \( \%REC \), main effects were obtained for raw material, \( F(1, 208) = 9.15, p < .01 \), and group, \( F(1, 10) = 6.56, p < .05 \), which also exhibited an interaction, \( F(1, 208) = 5.63, p < .05 \). Post-hoc analyses indicated that when glass was used, difference between groups was significant, where \( \%REC \) was lower for LQ than for HQ, \( p < .01 \), suggesting that there was less repeatability of states in the dynamics of hammering movement for LQ than HQ. Only the hammering movement of HQ differentiated the material used, in which the greater proportion of recurrence (higher \( \%REC \)) was found for the glass condition compared to the stone condition, \( p < .001 \) (Fig. 11A).

In the ANOVA on \( L_{\text{max}} \), all three factors were significant: sub-goal, \( F(1, 204) = 6.96, p < .01 \), raw material, \( F(1, 205) = 11.81, p < .01 \), and group, \( F(1, 10) = 6.56, p < .05 \). The raw Material \( \times \) Group interaction, \( F(1, 205) = 9.25, p < .01 \) as well as the three-way interaction, \( F(1, 204) = 9.67, p < .01 \), were also significant. Post-hoc analyses indicated that when glass was used, the hammering movement of HQ was more dynamically stable (longer \( L_{\text{max}} \)) than LQ in both sub-goals, \( p < .05 \), whereas when stone
was used, this was the case only during fluting, \( p < .05 \). Inspection of Fig. 11B suggests that \( L_{\text{max}} \) was considerably low when LQ was calibrating glass. This impression was confirmed by the post hoc analysis that revealed \( L_{\text{max}} \) was significantly lower in LQ during calibration using glass than all the other comparable conditions, \( p < .05 \). Except for calibration sequence of LQ, the dynamics of the hammering movement was more dynamically stable (longer \( L_{\text{max}} \)) for the glass condition compared to the stone condition, \( p < .01 \).

An ANOVA on \%DET found main effects of sub-goal, \( F(1, 203) = 98.89, p < .001 \), and group, \( F(1, 10) = 17.87, p < .01 \). All interactions were significant: sub-goal by material, \( F(1, 203) = 6.13, p < .05 \), sub-goal by group, \( F(1, 203) = 30.42, p < .001 \), raw material by group, \( F(1, 205) = 13.11, p < .001 \), and the three-way interaction, \( F(1, 204) = 16.39, p < .001 \). Post-hoc analyses indicated that the dynamics of the displacement of the hammering hand of HQ was more deterministic (higher \%DET) than those of LQ in all conditions, \( p < .05 \) (Fig. 11C). When glass was used, \%DET of HQ significantly increased whereas that of LQ significantly decreased compared to when stone was used, \( p < .01 \). In addition, \%DET was significantly greater during fluting compared to calibration, \( p < .01 \), except for glass condition in HQ (Fig. 11C). All remaining effects were nonsignificant.

### 3.3. Postural hand

#### 3.3.1. Position in vertical direction

In the ANOVA on \( M_{zp} \), main effects were obtained for sub-goal, \( F(1, 203) = 22.29, p < .001 \), raw material, \( F(1, 203) = 85.41, p < .001 \), and group, \( F(1, 10) = 5.01, p = .049 \). Sub-goal and raw material

![Fig. 12. Means of dependent measures of the postural hand calculated for each 30-s sequence: (A) mean vertical position, (B) standard deviation of vertical position, (C) mean resultant velocity, and (D) standard deviation of resultant velocity. Error bars represent standard errors of the means.](image-url)
both exhibited interactions with group: sub-goal by group, $F(1, 203) = 31.83, p < .001$, and raw material by group, $F(1, 203) = 17.68, p < .001$. Post-hoc analyses indicated that HQ differentiated $M_{zp}$ both across sub-goals and across raw materials, $p < .001$, while craftsmen in LQ differentiated $M_{zp}$ across raw materials, $p < .001$, but not across sub-goals (Fig. 12A).

An ANOVA on $SD_{zp}$ found a main effect of sub-goal, $F(1, 204) = 28.78, p < .001$, as well as sub-goal by group interaction, $F(1, 204) = 8.95, p < .01$. A post hoc analysis indicated that the position of the postural hands of HQ was significantly more variable during fluting compared to calibration, $p < .001$, suggesting the clear distinction of the movement of the postural hand of HQ across the two sub-goals (Fig. 12B).

### 3.3.2. Resultant velocity

In the ANOVA on $M_{vp}$, a main effect was obtained for sub-goal, $F(1, 204) = 9.8, p < .01$. Sub-goal and raw material both exhibited interactions with group: sub-goal by group, $F(1, 204) = 7.45, p < .01$, and raw material by group, $F(1, 205) = 6.21, p < .05$. The three-way interaction was also significant, $F(1, 204) = 9.21, p < .01$. As shown in Fig. 12C, the velocity of the postural hands of LQ was significantly lower than that of fluting by LQ in glass condition of LQ, $p < .001$, and that of calibration by LQ in stone condition of LQ, $p < .01$, and that of calibration by HQ in glass condition, $p < .05$. These results suggest that the postural hands of LQ remained relatively still when unfamiliar glass was used.

$SD_{vp}$ was greater during fluting compared to calibration, $F(1, 204) = 12.49, p < .01$. In the ANOVA, interaction between raw material and group was also significant, $F(1, 207) = 5.77, p < .05$. A post hoc analysis indicated that the postural hands of HQ moved with greater variability in velocity when glass was used than when stone was used, $p < .05$ (Fig. 12D).

---

**Fig. 13.** Means of RQA measures of the postural hand calculated for each 30-s sequence: (A) $%REC$, (B) $%DET$, and (C) $L_{max}$ as a function of sub-goals, skill level groups and raw materials. Error bars represent standard errors of the means.
3.3.3. RQA

In the ANOVA on %REC of the vertical displacement of the postural hand, a main effect for raw material, \( F(1, 207) = 10.11, p < .01 \), two-way significant interaction between sub-goal and group, \( F(1, 204) = 29.39, p < .001 \), and between raw material and group, \( F(1, 207) = 4.48, p < .05 \), and the three-way interaction, \( F(1, 204) = 6.62, p < .05 \), were obtained. The differences between sub-goals were significant in the glass condition for both groups, \( p < .05 \), but in a contrary manner. As shown in Fig. 13A, during the calibration sequence in glass condition of LQ, %REC was significantly higher than all other comparable conditions, \( p < .001 \). This result is likely to be related to the very static postural hand of LQ in this particular condition (Fig. 12C).

The dynamics of the displacement of the postural hand was less sensitive to perturbations (longer \( L_{max} \)) during fluting compared to calibration, \( F(1, 205) = 4.88, p < .05 \), and when glass was used than when stone was used, \( F(1, 209) = 6.58, p < .05 \) (Fig. 13B).

The dynamics of the displacement of the postural hand was more deterministic (higher %DET) when glass was used than when stone was used, \( F(1, 206) = 4.43, p < .05 \) (Fig. 13C). All remaining effects were nonsignificant.

3.4. Influence of hammering hand on postural hand

We wanted to know whether the displacement of the postural hand was due to the shock of the hammer impact, or due to other factors such as adjusting the position of a roughout to prepare for the strike. If the former was the case, then the resultant velocity of the postural hand should be positively correlated with the impact force of the hammer. We did not measure the force of the hammer impact. However, in percussion tasks such as golf putting (Craig, Delay, Grealy, & Lee, 2000) and stone knapping (Bril, Rein, Nonaka, Wenban-Smith, & Dietrich, 2010), the amplitude of the striking movement has been shown to be scaled according to the required amount of kinetic energy at impact. We obtained similar results that the amplitude of oscillation of the hammering hand was significantly smaller when relatively fragile glass was used than when stone was used, implying that the amplitude of the movement of the hammering hand reflected the force applied at impact. As such, it seemed reasonable to examine the correlation between \( M_{ah} \) and \( M_{vp} \) to explore the influence of the impact force on the displacement of the postural hand. The results are shown in Fig. 14, in which each dot represents a 30-s sequence. A linear regression revealed that in LQ \( M_{vp} \) reliably increased as \( M_{ah} \) increased, \( F(1, 110) = 104.97, p < .001, r^2 = .49, M_{vp} = .09 M_{ah} + 1.59 \), whereas there was no significant correlation in HQ. The resultant velocity of the postural hands of LQ reflected the amplitude of movement of the hammering hand, while that was not the case in HQ.

![Fig. 14. Mean resultant velocities of the postural hand in each 30-s sequence as a function of mean amplitude of the hammering hand.](#)
4. Discussion

We investigated bimanual coordination in a goal-directed tool use task in which the two hands' activities are asymmetrical and highly specialized. The movements of the two hands and the coordination between them were evaluated with respect to the recurrence of states (indexed by %CREC and %REC), deterministic structure (indexed by %CDET and %DET), and robustness to perturbation (indexed by CLmax and Lmax) of the dynamics, as well as more conventional measures such as means and standard deviations of the amplitude and period of oscillation of the hammering hand, and the position and velocity of the postural hand within each sequence. The central issues of the current experiment were how the movements of unilateral hands were nested into bimanual coordination, and how the behavior of bimanual coordination was embedded in the context of the task. Previous research (Biryukova & Bril, 2008; Bril et al., 2005; Roux et al., 1995) led us to predict that: (1) there would be more stable and more deterministic coupling between the hands of experts than non-experts, (2) both bimanual coordination and unilateral movement would specify the functional demands of the task, and (3) the introduction of the novel material would disrupt the control of movement of LQ, while that of HQ would be stable regardless of the material used.

4.1. How the control of unilateral movement was nested into bimanual coordination?

To remove a flake by hammer percussion, it is necessary to control the kinetic energy of the hammer at impact. The analysis of the hammering hand found that the amplitude of hammering movement varied according to the material used (which require different amounts of impulse to realize the affordances for flaking), where the amplitude of oscillation was smaller when relatively fragile glass was used than when stone was used (Fig. 10A). The difference in amplitude across sub-goals was not as obvious. Although fluting requires greater impulse, extracted fluting sequences included preparatory oscillations of the hammer as well as a few actual strikes. Naturally, we found significantly greater variability in both amplitude and frequency when they were fluting than when they were calibrating (Fig. 10B and D), and averaging them within a sequence may have masked the difference of actual striking amplitude between fluting and calibration.

In addition to the control of the hammering movement, what is also necessary is the control of the postural hand to position and stabilize the object to be hit. As the amplitude of the hammering movement increased, the mean resultant velocity of the postural hand also reliably increased for LQ, but this was not the case for HQ (Fig. 14). Yet, mean resultant velocity of the postural hand was not different across the two groups (Fig. 12C). These results suggest that the velocity of the postural hand of the craftsmen from HQ was relatively independent of the kinetic energy transmitted by the hammer. In order to transmit the kinetic energy of the hammer to a roughout efficiently, the hand holding the roughout should not be perturbed greatly by the shock of impact. Thus, the independence of the movement of the postural hand from the amplitude of the hammering hand found in HQ has a functional significance, and may indicate an aspect of dexterity of highly skilled experts from HQ. It was also found that only HQ craftsmen manipulated the roughout in a clearly distinct manner across the two sub-goals (Fig. 12A and B), which may have reflected the adjustments to different percussive forces involved in the two sub-goals.

CRQA on the pairs of displacement signals found a significantly greater %CDET for HQ than for LQ (Fig. 9C). As mentioned in introduction, recurrence methods do not provide an exact formulation of state variables underlying a system’s behavior. However, inferences can be made based on the overall features of the system’s dynamics extracted by recurrence methods. Mathematically speaking, high %CDET indicates that deterministic rules are present in the dynamics of shared states between the two movement trajectories in the reconstructed phase space. In the present experiment, given the fact that the velocity of the postural hand was not reliably related to the amplitude of the hammering movement in HQ (Fig. 14), the possibility that the greater amount of observed deterministic structure of the dynamics of bimanual coordination in HQ compared to LQ stems from the perturbation caused by the mechanical impact may be excluded. One remaining possibility is that such regularity of the displacement of the two hands in HQ emerged from the control of bimanual action, in which the
activity of the postural hand to position and orient the object to be hit and that of the hammering hand to deliver a blow are coupled in a coherent manner.

Replicating the result of CRQA, RQA on the hammering hand revealed that the dynamics of the displacements of the hammering hand of HQ was more deterministic and recurrent than those of LQ. At the same time, HQ exhibited a tendency to move their hammering hand with greater variability in amplitude and frequency than LQ, in line with the results of Biryukova and Bril (2008). These results suggest that the observed deterministic structure of the dynamics does not stem from the stereotypy of the movement of the hammering hand. Or, conversely, the variability of the amplitude and frequency of hammering movement was not of random origin. We also observed a similar tendency in the postural hand, where the dynamics of the displacement of the postural hand tended to be more deterministic for HQ compared to LQ, although the effect was not statistically significant presumably due to the ceiling effect (i.e., values may be too close to the ceiling of 100% to allow a significant amount of variability). The fact that, for HQ, relatively greater amount of deterministic structure of the dynamics was found in the displacement of each hand as well as the coupling between them implies that such characteristics may not reside in the intrinsic dynamics of either hand alone. What seems likely is that the deterministic structure of the dynamics of the displacement of each hand reflected the overall behavior of a bimanual system in which it was embedded.

Mitra et al. (1998) argued that motor learning involves the process of forming a coordinative structure, and then building more determinism into those dynamics by reducing the noise output of the coordinative structure. The observed fact that the dynamics of bimanual movement coordination was more deterministic in HQ than in LQ seems to be in line with their argument. However, it should also be noted that there is a fundamental difference in the task under study. The task of the participants in Mitra et al.’s (1998) experiment was to learn how to produce a novel interlimb rhythmic coordination at a relative phase of 90°. In contrast, the task of craftsmen in the current experiment was not to produce a stereotyped pattern of movement, but to produce an ellipsoidal pattern with different raw materials. In the current experiment, it is not true that the craftsman learned to displace his or her body in a certain manner as the participants did in Mitra et al.’s (1998) study. Both in Biryukova and Bril (2008) and the current experiment, the indexes of variability of movement trajectories were shown to increase as a function of the level of expertise. Clearly, there is a need to examine more carefully the relation between learning of movement coordination and learning of goal-directed action (cf., Bernstein, 1967, 1996; Nonaka & Sasaki, 2009; Reed, 1982; Reed & Bril, 1996). Hence, generalization about movement organization will require experimental testing under different functional circumstances.

4.2. How the control of movement was embedded in the context of the task?

Just as the control of unilateral movement was embedded in the context of the behavior of a bimanual system, so was the behavior of a bimanual system embedded in the context of the function performed in the world. CRQA revealed an aspect of skill-level difference in the functional specificity of bimanual coordination. Only in HQ, greater degree of shared activity of the two hands (greater %CREC) was found when they were fluting than when they were calibrating (Fig. 9A), and the trajectories diverged less over time (longer CLmax) during fluting than during calibration (Fig. 9B). These results suggest that only in HQ, switches in the sub-goal affected the dynamics of bimanual coordination, in such a way to decrease the noise magnitude and the sensitivity to perturbation during fluting. Fluting is said to be the most critical phase in stone bead production, as subtle disruptions in fluting may result in failure of the entire task (Roux et al., 1995). On the other hand, calibration, a process of standardization of the uneven surfaces to make available the affordances for fluting, requires flexibility. The characteristics of HQ craftsmen that the dynamics of bimanual coordination is more stable and less noisy during fluting compared to calibration specify such different functional requirements of sub-goals.

In contrast, the bimanual movement coordination of LQ did not exhibit a statistically significant difference in the magnitude of noise or dynamical stability between the two sub-goals. Although statistically not significant, contrary to HQ, the movements of the two hands of LQ tended to exhibit greater proportion of shared states (greater %CREC) when they were fluting than when they were...
calibrating, especially when LQ used glass. Yet, at the same time, when glass was used, the shared activity between the movements of the two hands had significantly less deterministic structure in the dynamics (lower %\text{CDET}) than the other conditions. Taken together, when LQ were calibrating glass roughouts, the increased shared states between the displacement signals of the two hands in the reconstructed phase space were not patterned over time. We will return to this point shortly and discuss the influence of the material used.

CRQA found that for both groups, the dynamics of the bimanual movement coordination tended to be more deterministic during fluting compared to during calibration, although the difference was only significant in glass condition (Fig. 9C). It seems that action was relatively constrained when craftsmen were fluting, which resulted in the regularity in the dynamics of bimanual coordination. RQA on the postural hand revealed that for both groups, the dynamics of the displacement of the postural hand was less sensitive to perturbations (longer $L_{\text{max}}$) during fluting compared to calibration (Fig. 13B). It is interesting to note that for LQ such differentiation did not appear at the level of bimanual coordination, while for HQ the characteristics of movement dynamics that differentiates between the two sub-goals was consistent across unilateral movement and bimanual coordination.

For HQ, the results of RQA on each hand generally exhibited the similar tendency to those of CRQA on bimanual coordination. The control of movement in HQ, both in unilateral and in bimanual coordination, exhibited more recurrence of states, more deterministic structure, and less sensitivity to perturbation in the dynamics during fluting compared to calibration, which reflects the functional requirements of the two sub-goals (e.g., Roux et al., 1995). These results of HQ seem to provide support for the argument that the functional specificity at two layers of movement control (i.e., unilateral and bimanual) may coexist (e.g., Domkin et al., 2002, 2005; Latash, 2008). Moreover, the comparison across groups suggests that the expertise may lie in the nesting of functionally specific adjustments at different levels of a control hierarchy (cf., Latash, 2008; Reed, 1988).

4.3. Influence of the material used

Previous studies (Bril et al., 2005; Roux et al., 1995) found that the performance of LQ was considerably deteriorated when the unfamiliar raw material (glass) was introduced. We found several characteristics of the movement of LQ that might be related to their decreased performance level. As mentioned above, when LQ used glass during calibration, there was an increase of shared states between the movements of the two hands that were not of deterministic origin. In this condition, the movements of the hammering hands of LQ tended to exhibit less variability in terms of amplitude and frequency, yet their dynamics was more sensitive to perturbation and less deterministic compared to the stone condition. One possible explanation for such change is that the trajectory of the movement got less variable so as to cope with its decreased regularity and stability in the dynamics when handling unfamiliar raw material. The postural hand seemed to be virtually frozen during calibration using glass (Fig. 12C), which accompanied highly significant increase of recurrent states (Fig. 13A). These results seem to suggest that the movement of the two hands got less flexible when LQ craftsmen were calibrating glass, which is likely to be related to the deteriorated performance of LQ in this unfamiliar situation reported in the previous studies (Bril et al., 2005; Roux et al., 1995).

In contrast, the displacement of the hammering hand of HQ was significantly more dynamically stable when they used glass than when they used carnelian stone (Fig. 11B), and HQ craftsmen moved their hammering hand with greater variability in frequency in the glass condition compared to the stone condition (Fig. 10D). These results suggest that the variability in hammering frequency for HQ was not due to increased noise or decreased stability (cf., Riley & Turvey, 2002). One possible explanation is that the increased proportion of recurrence ($\%\text{REC}$), dynamical stability ($L_{\text{max}}$) and the variability of oscillation frequency ($\text{SD}_{pn}$) of the hammering hand in the glass condition for HQ are related to the constraints posed by the fragility of glass which demanded more precise fine-tuning of the impact velocity and the point of percussion compared to the raw material craftsmen were familiar with. The results of the postural hand also support this interpretation. Replicating the result of CRQA on bimanual coordination, RQA on the postural hand revealed that for both groups, the dynamics of the displacement of the postural hand was less sensitive to perturbations when fragile glass was used than when carnelian stone used (Fig. 13B).
In general, when glass was used, the difference in the movement of HQ between the two sub-goals was more exaggerated than when stone was used, in which greater regularity and dynamical stability were found when they were fluting than when they were calibrating. These results seem to imply that the characteristics of the movement of HQ were a function of the degree of stabilization required for the performance of the sub-goal in different environmental situations (see Balasubramaniam, Riley, & Turvey, 2000; Stoffregen, Smart, Bardy, & Pagulayan, 1999 for similar discussion on postural control).

5. Conclusion

We studied asymmetric bimanual coordination of professional bead craftsmen from two skill level groups in a naturalistic situation using recurrence methods. Our key findings are that the movements of the two hands of experts were functionally linked, reflecting the roles assumed by each hand, and that the skill level difference appeared not only in the movements of the individual hands, but also in the way they were organized into a unified act. Regarding the functional specificity, among others, evidence was found that only the bimanual movement coordination of highly skilled experts (HQ) specified the different functional requirements of the two sub-goals, in which the dynamics of bimanual coordination was more stable and less noisy during fluting compared to calibration. Furthermore, confirming our hypothesis, the dynamics of bimanual movement of high level experts (HQ) exhibited more deterministic coupling than that of lower level craftsmen (LQ). These results suggest that expertise in this skilled bimanual action lies in the nesting of functionally specific adjustments at different levels of a control hierarchy, in which movements of the two hands are modulated in such a way to meet the various functional demands of the situation.

Acknowledgments

The authors are grateful to Valentine Roux for organizing the experiment in Khambhat and for supporting our methodological approach to data analysis. They also would like to thank Agnès Roby-Brami, Elena Biryukova, and Gilles Dietrich for their invaluable help for data acquisition recordings, and Gérald Monthel for the drawings of Figs. 1 and 3. This research was funded by the European Commission (Sixth Framework Programme Project 29065 HANDTOMOUTH), and the French Ministère délégué à la recherche et aux nouvelles technologies (ACI TTT P7802 n° 02 2 0440). The first author is grateful to the instructors at APA Advanced Training Institutes 2006 “Nonlinear Methods for Psychological Science” for their guidance on recurrence methods. An earlier version of this article was improved by the suggestions of two anonymous reviewers.

References


