Developmental Characteristics of Disparate Bimanual Movement Skills in Typically Developing Children

Authors: Julian Rudisch (1), Jenny Butler (1), Hooshang Izadi (2), Deirdre Birtles (3), Dido Green (1)

Affiliations:

1) Department of Sport and Health Sciences, Oxford Brookes University, Oxford, UK
2) Department of Mechanical Engineering and Mathematical Sciences, Oxford Brooks University, Oxford, UK
3) School of Psychology, University of East London, London, UK

Abstract

Mastery of many tasks in daily life requires role differentiated bimanual hand use with high spatiotemporal cooperation and minimal interference. In this study, we investigate developmental changes in the performance of a disparate bimanual movement task requiring sequenced movements. Age groups are attributed to changes in central nervous system structures critical for bimanual control such as the corpus callosum and the prefrontal cortex; young children (5-6 years), older children (7-9 years) and adolescents (10-16 years). Results show qualitative changes in spatiotemporal sequencing between the young and older children which typically marks a phase of distinct reduction of growth and myelination of the CC. Results show qualitative changes in spatiotemporal sequencing between the young and older children which coincides with distinct changes in the growth rate and myelination of the CC. The results further support the hypothesis that CC maturation plays an important role in the development of bimanual skills.

Keywords

Bimanual Coordination, Kinematics, Motor Development, Corpus Callosum

Introduction

In combination with the development of their (uni-) manual skills as a result of their upright posture, humans have also developed the remarkable ability to incorporate both hands simultaneously into complex bimanual tasks. The majority of bimanual tasks we encounter during daily life, such as opening jars or bottles, using cutlery or playing musical instruments usually require disparate actions of the two hands, i.e. role differentiated bimanual movements (RDBM) (Gonzalez & Nelson, 2015). Even though they perform different actions, movement of both hands seems to be organised as a single unit in which the timing and position of the movement of one hand are aligned to the spatiotemporal demands of the opposing hand (Kelso, Putnam, & Goodman, 1983). Guiard (1987) proposes the theory of an asymmetric division of labour in RDBM in which one hand acts as a frame of reference (the holding or stabilising hand) the other hand has to adjust to (the manipulating hand). During infant development of RDBM, the non-dominant hand begins to take over holding and stabilising roles while the dominant hand performs the manipulating actions (Kimmerle, Ferre, Kotwica, & Michel, 2010).

Disparate bimanual actions cannot always be clearly differentiated into a holding/stabilising and a manipulating part. Sequenced movements, such as opening a drawer and retrieving an object from inside requires two manipulating actions. However, Guiard's (1987) theory may still apply if the movement of the leading hand (the hand performing the first part of the sequence) acts as a spatiotemporal frame of reference to facilitate the temporal sequencing. Wiesendanger, Kazennikov, Perrig & Kalzuny (1996) have shown that adults performing such a drawer task prefer to use their non-dominant hand for the opening of the drawer. Using a similar paradigm requiring opening a box with one hand to retrieve an object with the other hand, Birtles et al (2011) have also demonstrated that adults preferably use their non-dominant hand for the box opening. Infants and younger children (up to 6 years) on the other hand have been shown to use reversed (i.e. leading with their non-dominant hand) or mixed strategies (Birtles et al., 2011; Ramsay & Weber, 1986). Further investigation of the kinematics of hand movement showed, that children complete the task in a more segmented fashion than adults with little or no overlap of the two hand actions (Birtles et al., 2011). Such segmented movement behaviour has also been shown in some children with unilateral Cerebral Palsy (Hung, Charles, & Gordon, 2004) whereas others have demonstrated interfering movement behaviour (where the two hands are activated nearly simultaneously) when using their impaired limb as the leading hand (Rudisch et al., 2016).

The exchange of information between hemispheres through the corpus callosum (CC) is crucial for spatial and temporal cooperation between hands, especially so for complex and disparate bimanual movements (Gooijers et al., 2014; Swinnen, 2002). The ability of temporal and spatial coupling of both hands seems to be particularly affected by the integrity of the CC (Gooijers et al., 2013; Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002), and thus may be considered a crucial factor for the sequencing of bimanual movements. Even though the CC shows further changes in size into adulthood (Keshavan et al., 2002), a distinct reduction of growth and myelination after the age of about 6 years has been reported (Tanaka-Arakawa et al., 2015; Uda et al., 2015). Information on hand function related to bimanual control may be processed in the areas of the frontal lobe, the supplementary motor area and the premotor cortex (Grefkes, Eickhoff, Nowak, Dafotakis, & Fink, 2008; Swinnen, 2002); areas particularly related to motor planning, sequencing of movements and more cognitive aspects of motor control. Activation within the prefrontal cortex (as well as the anterior part and vermis of the cerebellum) has been shown to be positively correlated with increasing spatiotemporal complexity of a movement task (Debaere, Wenderoth, Sunaert, Van Hecke, & Swinnen, 2004). The grey matter development of the frontal lobe is reported to reach its peak around the age of 10 years, with a male and female difference evident (Gogtay & Thompson, 2010).

While bimanual movements are already observable at a very young age (i.e. birth to 1 year of age) these tend to reflect spontaneous or reflexive activation rather than voluntary goal directed actions. Trajectories of the hands of such early bimanual coordination patterns tend to be synchronous (Corbetta & Thelen, 1996). Role differentiated use of the hands usually starts to develop after the first year in an infant's life (Gonzalez & Nelson, 2015; Kimmerle et al., 2010; Ramsay & Weber, 1986) continuing through to early childhood (Babik & Michel, 2015; Birtles et al., 2011; Ramsay & Weber, 1986). Although de Boer et al., (2012) demonstrated changes in the dynamics of bimanual coordination into adulthood, less is known regarding developmental aspects of temporal-spatial control of divergent bimanual movements.

This study therefore set out to investigate differences in the performance of a disparate bimanual box opening task requiring sequenced movements of both hands. Differences were investigated: i) Between conditions when the dominant or non-dominant hand acts as the frame of reference; ii) Between bimanual and decomposed unimanual movements; and, iii) Across different developmental stages.

Methods

The study was approved by the Oxford Brookes University Research Ethics Committee (UREC 130713).

Participants

Participants were recruited and tested during a University open-day event for the general public. Potential participants (and parents of children <16 years) received an information sheet about the study and signed informed consent prior to participation. Handedness was determined prior to performing the experimental task, using the Edinburgh handedness inventory (Oldfield, 1971).

A total of 37 children (14 male) between 5 and 16 years of age ($\bar{x}$=8.3, SD=2.3) participated in this study. Twenty-nine (78%) of the participants were classified as right handed. In view of developmental characteristics of neural structures that play essential parts in inter-limb coordination (CC and prefrontal cortex), performance was investigated in three different age groups: young children (YC) 5-6 years, older children (OC) 7-9 years and adolescents (AD) 10-16 years). Group characteristics of the three age bands are presented in Table 1.

Procedures

Participants performed a bimanual box opening task that required role differentiated bimanual hand movements (see Rudisch et al., 2016 for more detailled description). To complete the bimanual box opening task, participants had to open the lid of a transparent box with one hand and press a button inside with the opposing hand (see Fig. 1). The task was performed in two bimanual conditions: Dominant Condition (DC), where the dominant hand was used to open the lid and the non-dominant hand to press the button, or the reverse, Non-dominant Condition (NC) where the non-dominant hand was used to open the lid. In addition, the task was decomposed into unimanual subtasks comprising of either only the lid opening, or reaching to press the button. Bimanual tasks were executed 5 times (in blocks of 3*DC, 3*NC, 2*DC, 2*NC) and unimanual subtasks twice for each condition, with DC and NC performed alternately. Repetitions were limited to avoid 'boredom' in view of the simplicity of the task and lack of observable reward. The total task took less than 10 minutes. The first trial for each of the conditions DC or NC in the bimanual task was excluded for analysis to account for the familiarization decrement.

Position and orientation of each hand was recorded at 120Hz, using the electromagnetic motion tracking system G4 (Polhemus, Colchester, VT, USA) with sensors placed dorsally across the 3rd metacarpal bone. Data was low-pass filtered using a second order Butterworth filter with a cut-off frequency of 15Hz. Subsequently spatiotemporal events i) start of first hand, ii) beginning of box opening, iii) end point of box opening, iv) start of second hand and v) button press (see Fig. 2) were extracted using a semi-automatic algorithm written in MATLAB R2014b. Temporal variables Total Task Duration (TTD), i.e. the time from start of first hand to button press), duration of lid opening (the first hand movement) and duration of button press (second hand movement) were extracted. In addition, the following variables of relative temporal cooperation were extracted: Temporal coupling i.e. the temporal difference between lid opening and onset of the second hand's movement with positive values indicating an early start of the second hand relative to the lid opening and negative values indicating a late start; Movement overlap i.e. the amount of time in which both hands are moving together; and, Goal Synchronisation i.e. the temporal difference between each hands end point. Path length i.e. the total path of the button press action and the number of zero crossings of the acceleration curve were extracted as measures of smoothness. Movements that are more jerky are characterised by multiple phases of acceleration and deceleration and will thus present more zero crossings in the acceleration profile.

Statistical Analysis

All statistical analyses were performed in R 3.1.2 (R Core Team, 2014). Descriptive statistics are presented as Mean and Standard Deviation (SD) for a single variable or mean difference (MD) ± SD for intra-individual differences between variables. The coefficient of variation (CV), calculated by dividing the standard deviation by the mean value for the 4 trials in each condition, was used as a relative measure for intra-individual variability.

Factorial mixed measures ANOVAs were used to test for differences between conditions DC and NC (within subjects), uni- or bimanual task execution (within subjects) and age groups YC, OC and AD (between subjects). T-tests with Bonferroni correction for multiple comparisons were used for post-hoc analysis between age groups.

Results

Task Duration

Results of TTD (and CV of TTD) are presented in Fig. 3. Duration of the disassembled subtasks lid opening as well as button press during uni- and bimanual task execution are presented in Table 2.

Total Task Duration

There was a significant effect of age on TTD (*F*(2,34)=6.26, *p*=.005). Post-hoc comparison showed that YC performed significantly slower than OC (*p*=.002) and AD (*p*<.001). No difference was found between OC and AD (p=1) (see Fig. 3a). Condition had a significant effect on CV of total task duration (Fig. 3b) with reduced variability in NC (*F*(1,34)=11.67, *p*=002. No effect of age was observed.

Duration of Lid Opening

There was a significant effect of age on the duration of lid opening (*F*(2,32)=5.72, *p*=.008). Post-hoc testing revealed reduced duration for YC compared to OC as well as AD (both *p*<.001) however no difference between OC and AD (*p*=1). In addition, significantly faster performance was observed for unimanual as compared to bimanual task execution (*F*(1,32)=5.55, *p*=.025) (see Table 2). No significant differences were found for CV of lid opening duration between groups or conditions.

Duration of Button Press

Duration of button press was not affected by age group or condition of execution. Significantly faster performance was however found during unimanual task execution (*F*(1,34)=87.89, *p*<.001) (see Table 2). CV of button press duration was significantly affected by age (*F*(2,34)=4.70, *p*=.016) which was mainly due to the decrease between YC and AD (*p*=.018). In addition participants showed decreased variability in NC (*F*(1,34)=8.65, *p*=.006) (see Table 2).

Summary

Overall, these findings show that AD and OC perform the task (and its subtasks) significantly faster than YC. The condition of execution (DC vs NC) had no effect on mean movement duration. However in DC movement duration was significantly more variable compared to NC across all age groups.

Parameters of Temporal Cooperation

Aspects of temporal sequencing between the two hands reflect the temporal cooperativity of the bimanual action. The results for temporal coupling as well as the CV are shown in Fig. 4. Table 3 shows the results for movement overlap and goal synchronisation.

Temporal Coupling

No differences were found for temporal coupling between age groups or conditions. Variability of temporal coupling was however significantly reduced in NC as compared to DC (*F*(1,34)=6.04, *p*=.019) (see Fig. 4).

Movement Overlap

Similarly to the results of temporal coupling, there was no effect of age or condition of execution on movement overlap. Likewise, variability of movement overlap was reduced in NC (*F*(1,34)=11.01, *p*=.002) (see Table 3).

Goal Synchronisation

No significant group or task differences were found for absolute values or CV of goal synchronization (Table 3).

Summary

Measures of temporal cooperation did not show any significant differences across age groups or between conditions. Only participants in YC showed a slight reduction of temporal coupling, movement overlap and goal synchronisation in DC. Similar to the temporal variables, variability of temporal sequencing was reduced in NC across all age groups.

Movement Trajectories

Results of path length of the button press hand movement during bimanual task execution are shown in Figure 5. Results of path length during unimanual execution as well as number of zero crossings of the acceleration profile during bi- and unimanual execution are presented in Table 4.

Path Length

A significant effect of age (*F*(2,34)=5.01, *p*=.012) on path length was shown. Post-hoc testing showing a decrease with increasing age groups reaching significance between OC and AD (*p*=.018) as well as between YC and AD (*p*<.001) however not between YC and OC. In addition, type of task (uni- or bimanual) had a significant effect on total path (*F*(1,34)=28.45, *p*<.001) with increased path length during unimanual execution. CV of path length was neither affected by group or condition of execution (see Fig. 5).

Proxy measure of Smoothness

Number of zero crossings in the acceleration profile were significantly affected by age (*F*(2,34)=11.776, *p*<.001) as well as type of task execution (*F*(1,34)=56.208, *p*<.001). In addition, an interaction effect between age and task type was found (*F*(2,34)=4.367, *p*=.021. Post-hoc testing revealed reduced number of zero crossings between YC and OC (*p*<.001) as well as between YC and AD (*p*<.001) however not between OC and AD. Inspection of the interaction effect revealed, that differences between uni- and bimanual task execution were greater for YC as opposed to OC and AD. Number of zero crossings was considerably smaller in unimanual task execution indicating smoother trajectories. CV of zero crossings was not affected by age or condition of execution (see Table 4).

Summary

With increasing age, the movement of the second hand (button press) followed a shorter path and was found to be smoother. Variability for path length was reduced in NC. Across all age groups, the path length was longer with smoother movement during unimanual as compared to bimanual task execution. Children in the youngest age group in particular demonstrated increased number of zero crossings in the acceleration profile in the bimanual task execution.

Discussion

In this study we explored developmental aspects relating to the execution of a disparate bimanual box opening task requiring sequencing of movements in typically developing children. The task required disparate bimanual actions in order to open the lid of a box with one hand and press a button inside with the opposing hand.

According to the asymmetric division of labour hypothesis (Guiard, 1987) the movement of one hand acts as a frame of reference that the other adjusts to. In sequenced bimanual movements, it seems apparent that movement of the leading hand is being used as the frame of reference. It has been shown that (at least in adults) the non-dominant hand is preferentially used to act as the leading hand (Birtles et al., 2011; Wiesendanger et al., 1996). Contrary to our hypothesis, a comparison of the conditions when the non-dominant or dominant hand took the leading role showed no difference in performance of the bimanual box opening task. Only variables of temporal cooperation (Temporal Coupling, Movement Overlap and Goal Synchronization) were slightly different (i.e. less coupled) for YC in condition DC. On the other hand less variability was observed in condition NC across all age groups, A reduction in variability might be an indicator of higher automatization of movements (Cohen & Sternad, 2009). The difference in variability between DC and NC might thus be an indicator that sequenced role differentiated bimanual tasks in daily life are usually carried out by the participants with their non-dominant hand contributing to the formation of higher automatization of movement patterns in this condition. This pattern seems well established in typically developing children by 5 years of age.

In order to evaluate the effect of bimanual (as opposed to unimanual) task execution on movement parameters, the decomposed subtasks (i.e. lid opening and button press) were executed in isolation. Comparison of movement duration and smoothness during, lid opening and button press in the two different tasks revealed some intriguing findings. While both, lid opening and button press seemed to be performed faster in the unimanual case, total Path length was increased. A possible explanation is that the movement path might be less spatially constrained during unimanual execution since the lid is already fully opened. Despite the higher path deviation however the movement is smoother in the unimanual condition as expressed by the smaller number of zero crossings in the acceleration profile. Across age groups the bimanual task execution led to decreased smoothness of movement. The difference was however considerably bigger for YC, indicating bimanual nature of the task particularly affects the movement trajectories of the YC.

Several distinct changes in the coordination of bimanual movement as a consequence of development have been reported on. Bimanual movements are already observable at a very young age (i.e. birth to 1 year of age). They result more from spontaneous activation or reflexes than being initiated voluntarily. In addition, early bimanual coordination patterns tend to be rather synchronous (Corbetta & Thelen, 1996). Role differentiated use of the hands usually starts to develop after the first year in an infant’s life (Kimmerle et al., 2010; Ramsay & Weber, 1986). At about 13 months of age there seems to be a shift in using the preferred over the non-preferred hand for the acquisition and manipulation of objects (Babik & Michel, 2015). After 6 years of age a shift has been reported from using the dominant hand (Birtles et al., 2011; Ramsay & Weber, 1986) towards using the non-dominant hand as a leading hand (Birtles et al., 2011; Kazennikov, Perrig, & Wiesendanger, 2002) in disparate bimanual sequenced movements. A closer look at the kinematics has also shown that such bimanual actions are more segmentally sequenced during childhood and become more (temporally) overlapping in adults (Birtles et al., 2011). Whether or not these changes occur gradually or suddenly at a certain age has not yet been demonstrated. We have thus been looking at changes in the performance across age groups that are related to characteristic time points in the development of central nervous structures that are of importance for the execution of bimanual tasks. These reflect changes in the structure and connectivity of the CC between early and middle childhood (between YC and OC) (Tanaka-Arakawa et al., 2015; Uda et al., 2015) and peak in frontal grey matter development in later childhood, between OC and AD (Gogtay & Thompson, 2010).

The pattern that becomes apparent shows that improvements can be mainly observed between the YC (5-6 years) group and the OC (7-9 years). Differences between OC and AD (10-16 years) group were mostly marginal. Especially performance variables of movement duration or smoothness improved between YC and OC. In addition, the movement smoothness of the second hand seemed to be particularly decreased during the bimanual (as opposed to the unimanual) task for YC. Variables that show the ability of temporal sequencing (Temporal Coupling, Movement Overlap and Goal Synchronisation) showed changes between YC and

OC however interestingly only in the dominant hand leading condition. In summary, the characteristic changes observed between YC and OC suggest that CC maturation and developmental changes in bimanual movement skills may be temporally linked.

Robertson (2001) has demonstrated, that bimanual cooperation for symmetric in-phase tasks is only poorly developed in children under 8 years of age. The elemental coordination mode seems to strongly depend on the interhemispheric transfer (Kennerley et al., 2002) and thus the maturation of the CC. De Boer (2012) on the other hand has shown that spatiotemporal coordination during more complex disparate bimanual tasks rather improve during later developmental stages. Experimental tasks of this group were however specifically facilitating bimanual interference, e.g. by performing two competitive unimanual movement patterns with each hand at the same time, such as drawing a circle with one and a line with the other hand. Our own experimental paradigm required disparate bimanual coordination yet being less likely to elicit bimanual interference due to the natural occurrence of this movement pattern in daily live. The main performance changes were found, between the young and middle group and thus before 7 years of age, corresponding more to the development of the CC than the frontal lobe. The variance within age groups in our study was however high. Possible reasons might be that i) maturation of the CC happens at different interindividual rates or ii) bimanual performance required for the bimanual box opening task depends not only on the corpus callosum but also on the quality of central networks involved in the execution of bimanual tasks.

Limitations

Some of the differences between conditions might have arisen from the fact that the execution order was not counterbalanced. Furthermore, the cross-sectional design only warrants tentative interpretation of the results. Especially the large share of female participants in OC might have influenced the results due to the slightly delayed development of CC maturation. Greater differences in temporal characteristics may have been elicited in a task placing more demands on divergent manipulative skills or precision of one or other of the hands. Longitudinal developmental studies as well as measures of brain activation and function may be appropriate for future studies to explain some of the variance between participants.

Conclusion

In the present study, we investigated the development of bimanual coordination skills during a disparate bimanual box opening task across different stages of development related to the maturation of the CC and the frontal lobe, both of which are of significance for bimanual movement tasks. We found that bimanual performance shows substantial improvements after 6 years of age including faster task execution, improvements in sequencing and increased smoothness. Previous studies have shown that this period marks the end of accelerated growth of the CC (Tanaka-Arakawa et al., 2015; Uda et al., 2015) which offers a possible explanation that changes in the performance of bimanual task execution are predominantly observed at this time. The results however need to be regarded tentatively due to the high variance between individuals. Intraindividual differences in the development of the CC or qualitative differences in the formation of neural networks related to bimanual coordination are suggested to explain the huge variance.

Acknowledgements

We would like to thank all the children and adolescents who participated in this study. In addition, we would like to thank Martine Øien and Dr Carolyn Mason for their help and support with the data collection.

This is an accepted manuscript of an article published by Taylor & Francis in Journal of Motor Behavior on 02/03/2017. The published article is available online at: http://www.tandfonline.com/10.1080/00222895.2016.1271302

References

Babik, I., & Michel, G. F. (2015). Development of role-differentiated bimanual manipulation in infancy: Part 2. Hand preferences for object acquisition and RDBM-continuity or discontinuity? *Developmental Psychobiology*, *58*(2), 257–67. Journal Article. http://doi.org/10.1002/dev.21378

Birtles, D., Anker, S., Atkinson, J., Shellens, R., Briscoe, A., Mahoney, M., & Braddick, O. (2011). Bimanual strategies for object retrieval in infants and young children. *Experimental Brain Research*, *211*(2), 207–218. Journal Article. http://doi.org/10.1007/s00221-011-2672-5

Cohen, R. G., & Sternad, D. (2009). Variability in motor learning: relocating, channeling and reducing noise. *Experimental Brain Research*, *193*(1), 69–83. Journal Article. http://doi.org/10.1007/s00221-008-1596-1

Corbetta, D., & Thelen, E. (1996). The developmental origins of bimanual coordination: A dynamic perspective. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(2), 502–522. Journal Article. http://doi.org/10.1037/0096-1523.22.2.502

de Boer, B. J., Peper, C. E., & Beek, P. J. (2012). Development of temporal and spatial bimanual coordination during childhood. *Motor Control*, *16*(4), 537–59. Journal Article. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/23162066

Debaere, F., Wenderoth, N., Sunaert, S., Van Hecke, P., & Swinnen, S. P. (2004). Cerebellar and premotor function in bimanual coordination: parametric neural responses to spatiotemporal complexity and cycling frequency. *NeuroImage*, *21*(4), 1416–27. Journal Article. http://doi.org/10.1016/j.neuroimage.2003.12.011

Gogtay, N., & Thompson, P. M. (2010). Mapping gray matter development:

implications for typical development and vulnerability to psychopathology. *Brain and Cognition*, *72*(1), 6–15. http://doi.org/10.1016/j.bandc.2009.08.009

Gonzalez, S. L., & Nelson, E. L. (2015). Addressing the gap: A blueprint for studying bimanual hand preference in infants. *Frontiers in Psychology*, *6*, 560. Journal Article. http://doi.org/10.3389/fpsyg.2015.00560

Gooijers, J., Caeyenberghs, K., Sisti, H. M., Geurts, M., Heitger, M. H., Leemans, A., & Swinnen, S. P. (2013). Diffusion tensor imaging metrics of the corpus callosum in relation to bimanual coordination: Effect of task complexity and sensory feedback. *Human Brain Mapping*, *34*(1), 241–252. Journal Article. http://doi.org/10.1002/hbm.21429

Gooijers, J., Leemans, A., Van Cauter, S., Sunaert, S., Swinnen, S. P., & Caeyenberghs, K. (2014). White matter organization in relation to upper limb motor control in healthy subjects: exploring the added value of diffusion kurtosis imaging. *Brain Structure & Function*, *219*(5), 1627–38. Journal Article. http://doi.org/10.1007/s00429-013-0590-y

Grefkes, C., Eickhoff, S. B., Nowak, D. a., Dafotakis, M., & Fink, G. R. (2008). Dynamic intra- and interhemispheric interactions during unilateral and bilateral hand movements assessed with fMRI and DCM. *NeuroImage*, *41*(4), 1382–1394. Journal Article. http://doi.org/10.1016/j.neuroimage.2008.03.048

Guiard, Y. (1987). Asymmetric division of labor in human skilled bimanual action: the kinematic chain as a model. *Journal of Motor Behavior*, *19*(4), 486–517. Journal Article. http://doi.org/10.1080/00222895.1987.10735426

Hogan, N., & Sternad, D. (2009). Sensitivity of smoothness measures to movement duration, amplitude, and arrests. *Journal of Motor Behavior*, *41*(6), 529–534.

Journal Article. http://doi.org/10.3200/35-09-004-RC

Hung, Y. C., Charles, J., & Gordon, A. M. (2004). Bimanual coordination during a goal-directed task in children with hemiplegic cerebral palsy. *Developmental Medicine and Child Neurology*, *46*(11), 746–753. Journal Article, Research Support, U.S. Gov't, P.H.S. http://doi.org/10.1111/j.1469-8749.2004.tb00994.x

Kazennikov, O., Perrig, S., & Wiesendanger, M. (2002). Kinematics of a coordinated goal-directed bimanual task. *Behavioural Brain Research*, *134*(1–2), 83–91. Journal Article. http://doi.org/10.1016/S0166-4328(01)00457-0

Kelso, J. A. S., Putnam, C. A., & Goodman, D. (1983). On the space-time structure of human interlimb co-ordination. *The Quarterly Journal of Experimental Psychology Section A*, *35*(2), 347–375. http://doi.org/10.1080/14640748308402139

Kennerley, S. W., Diedrichsen, J., Hazeltine, E., Semjen, A., & Ivry, R. B. (2002). Callosotomy patients exhibit temporal uncoupling during continuous bimanual movements. *Nature Neuroscience*, *5*(4), 376–381. Journal Article. http://doi.org/10.1038/nn822

Keshavan, M. S., Diwadkar, V. A., DeBellis, M., Dick, E., Kotwal, R., Rosenberg, D. R., … Pettegrew, J. W. (2002). Development of the corpus callosum in childhood, adolescence and early adulthood. *Life Sciences*, *70*(16), 1909–22.

Kimmerle, M., Ferre, C. L., Kotwica, K. a., & Michel, G. F. (2010). Development of role-differentiated bimanual manipulation during the infant's first year. *Developmental Psychobiology*, *52*(2), 168–180. Journal Article. http://doi.org/10.1002/dev.20428

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113. Journal Article. http://doi.org/10.1016/0028-3932(71)90067-4

R Core Team. (2014). R: A Language and Environment for Statistical Computing. Vienna, Austria.

Ramsay, D. S., & Weber, S. L. (1986). Infants’ hand preference in a task involving complementary roles for the two hands. *Child Development*, *57*(2), 300–307. Journal Article. http://doi.org/10.2307/1130585

Robertson, S. D. (2001). Development of bimanual skill: the search for stable patterns of coordination. *Journal of Motor Behavior*, *33*(2), 114–26. http://doi.org/10.1080/00222890109603144

Rudisch, J., Butler, J., Izadi, H., Zielinski, I. M., Aarts, P., Birtles, D., & Green, D. (2016). Kinematic parameters of hand movement during a disparate bimanual movement task in children with unilateral Cerebral Palsy. *Human Movement Science*, *46*, 239–250. http://doi.org/10.1016/j.humov.2016.01.010

Swinnen, S. P. (2002). Intermanual Coordination: From Behavioural Principles To Neural-Network Interactions. *Nature Reviews. Neuroscience*, *3*(5), 348–359. Journal Article. http://doi.org/10.1038/nrn807

Tanaka-Arakawa, M. M., Matsui, M., Tanaka, C., Uematsu, A., Uda, S., Miura, K., … Noguchi, K. (2015). Developmental changes in the corpus callosum from infancy to early adulthood: a structural magnetic resonance imaging study. *PloS One*, *10*(3), e0118760. http://doi.org/10.1371/journal.pone.0118760

Uda, S., Matsui, M., Tanaka, C., Uematsu, A., Miura, K., Kawana, I., & Noguchi, K. (2015). Normal development of human brain white matter from infancy to early adulthood: A diffusion tensor imaging study. *Developmental Neuroscience*, *37*(2), 182–194. http://doi.org/10.1159/000373885

Wiesendanger, M., Kazennikov, O., Perrig, S., & Kaluzny, P. (1996). Two hands - one action: the problem of bimanual coordination. In A. Wing, P. Haggard, & J. R. Flanagan (Eds.), *Hand and Brain: The neurophysiology and psychology of hand movements.* (pp. 283–300). San Djego: Academic Press.

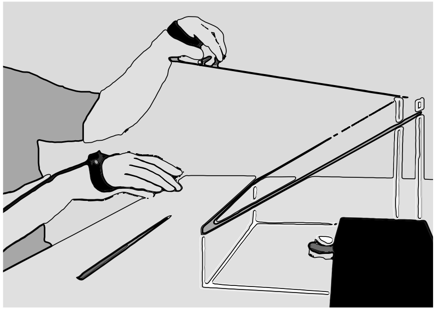

Fig. 1 Schematic illustration of the Bimanual Box-Opening Task. Participants are required to place their hands at the line and subsequently to open the box with one hand and press the button inside with the opposing. Tethered electromagnetic sensors are attached to the back of each hand. The electromagnetic source is placed next to the box (black cube)

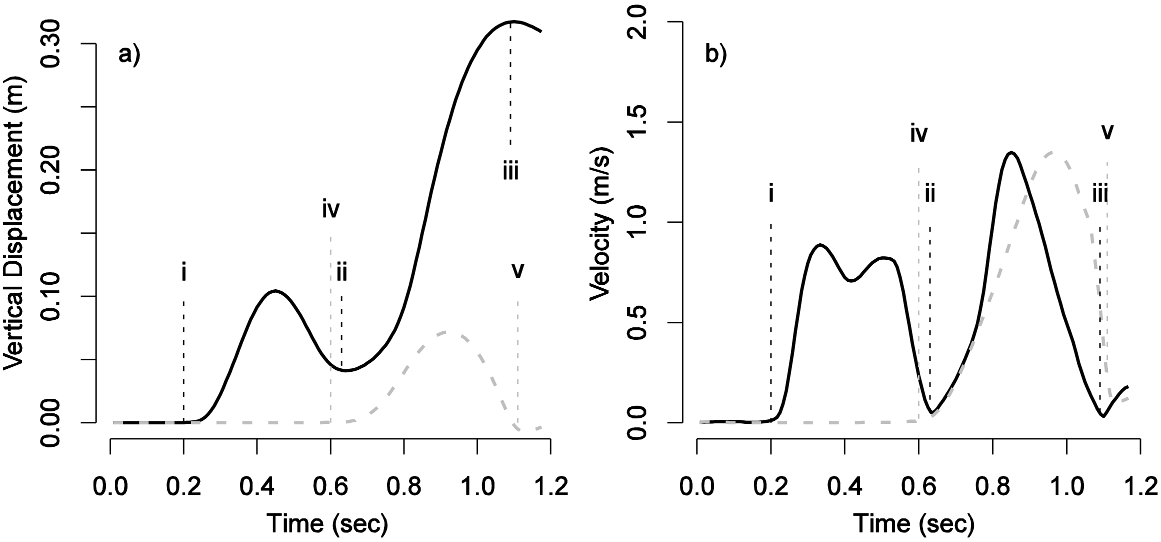

Fig. 2 Vertical displacement (a) and velocity profiles (b) of the lid opening (black solid line) and button press (grey dashed line) movement. The events i) start of first hand, ii) start of lid opening, iii) end of lid opening, iv) start of second hand were derived from characteristic features in the signal. The button press (event v) was derived from a digital signal from the button

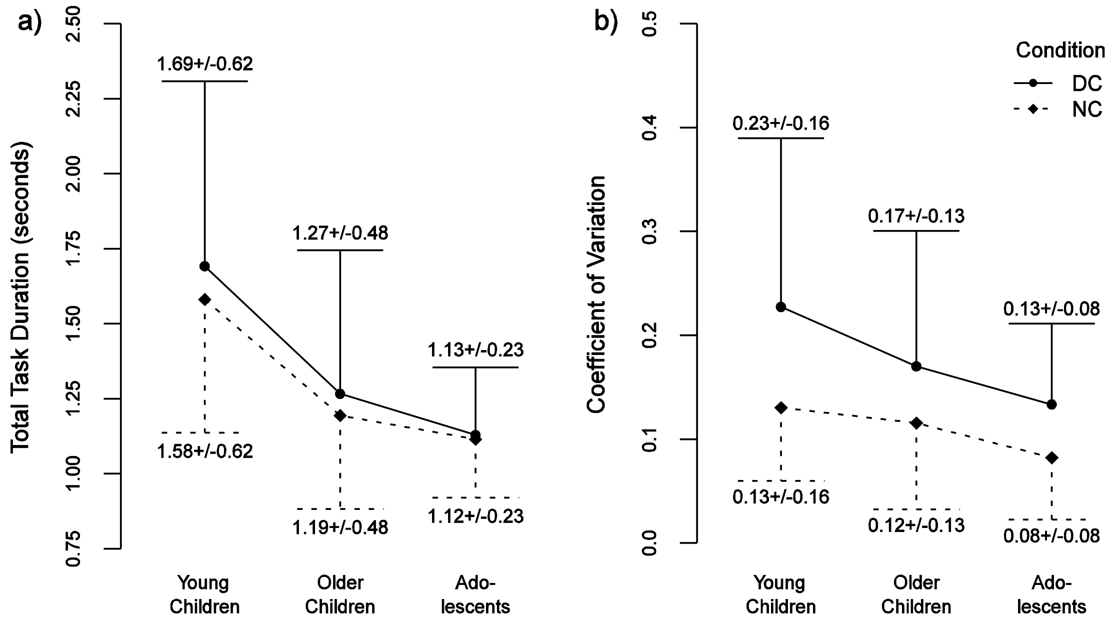

Fig. 3 Mean and Standard Deviation (Error Bars) of Total Task Duration (a) as well as Coefficient of Variation of Total Task Duration (b) according to the condition of execution (DC = Dominant Hand Condition; NC = Non-Dominant Hand Condition) and age group. Actual corresponding values are printed above or below the error bars to allow for better comparison

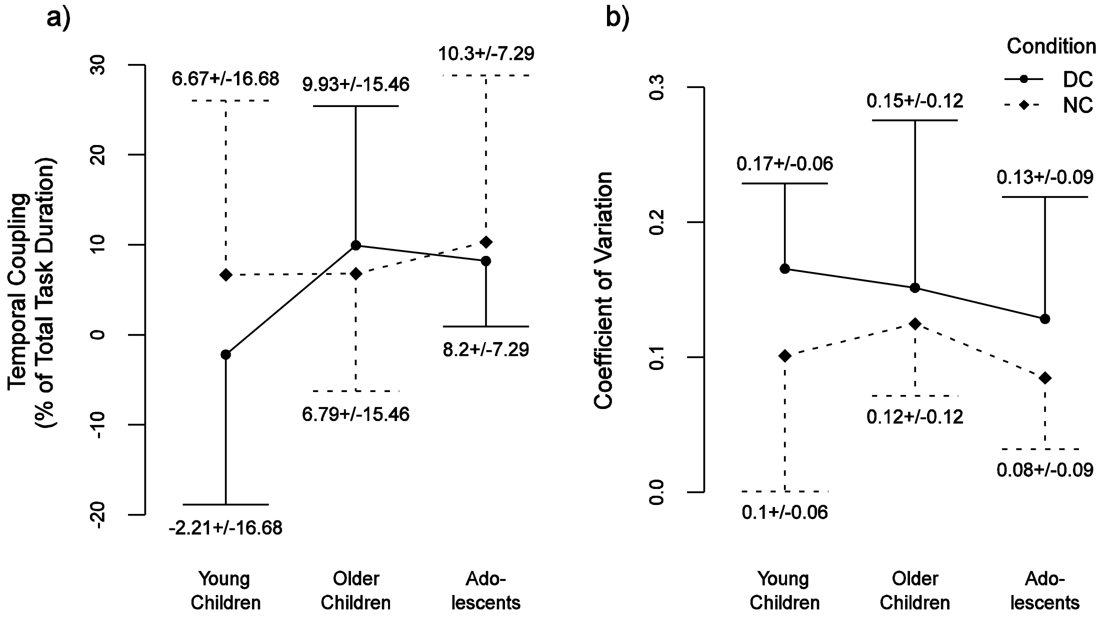

Fig. 4 Mean and Standard Deviation (Error Bars) of Temporal Coupling (a) as well as Coefficient of Variation of Temporal Coupling (b) according to the condition of execution (DC = Dominant Hand Condition; NC = Non-Dominant Hand Condition) and age group. Actual corresponding values are printed above or below the error bars to allow for better comparison

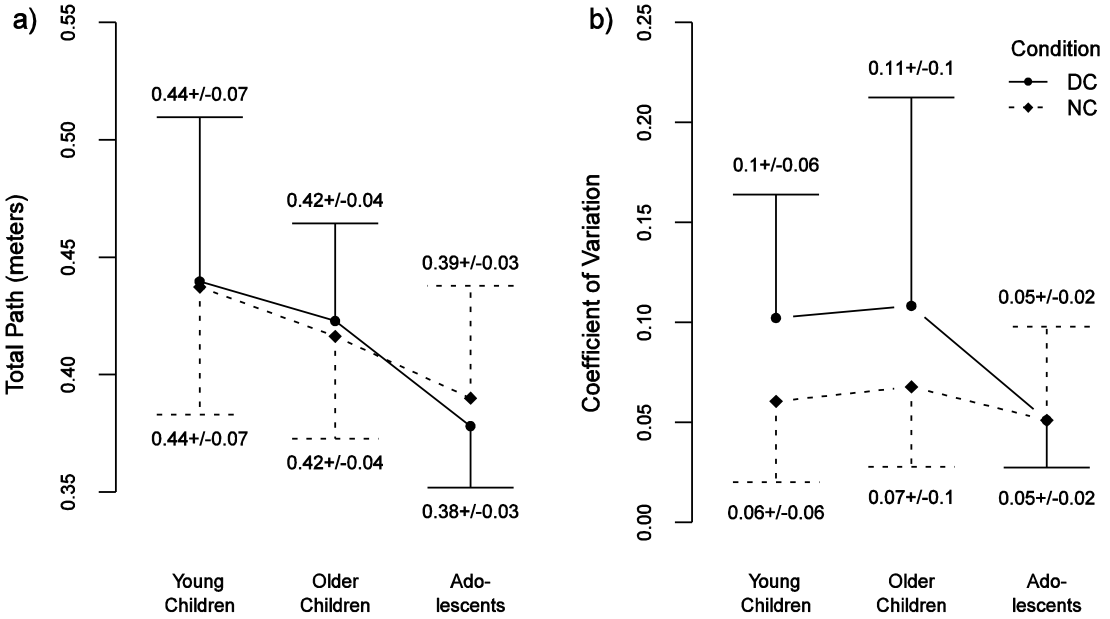

Fig. 5 Mean and Standard Deviation (Error Bars) of path length (a) as well as CV (b) according to the condition of execution (DC = Dominant Hand Condition; NC = Non-Dominant Hand Condition) and age group. Actual corresponding values are printed above or below the error bars to allow for better comparison

Table 1 Participants' Gender and Handedness by age band

Group (n)	Age Band (years)	Gender (m/f)	Handedness (r/l)
YC (15)	5 - 6	7/8	11/4
OC (13)	7 - 9	3/10	11/2
AD (9)	10 - 16	4/5	7/2

YC = Young Children, OC = Older Children, AD = Adolescents, m=male, f=female, r=right (handed), l=left (handed)

Table 2 Mean (SD) of absolute values and CV of variables reflecting task duration of the disassembled subtasks lid- opening and button press during uni- and bimanual task execution according to condition and different age bands

	DC			NC		
	Young Children	Older Children	Ado-lescents	Young Children	Older Children	Ado-lescents
DLO (s)	1.42 (0.41)	1.13 (0.33)	1.04 (0.16)	1.46 (0.38)	1.11 (0.24)	1.05 (0.14)
DLO_{Uni} (s)	1.28 (0.39)	1.07 (0.38)	1.03 (0.19)	1.17 (0.32)	1.06 (0.22)	1.01 (0.15)
CV DLO	0.22 (0.16)	0.13 (0.10)	0.13 (0.07)	0.16 (0.09)	0.10 (0.10)	0.10 (0.11)
DBP (s)	0.88 (0.24)	0.81 (0.26)	0.73 (0.12)	0.90 (0.38)	0.72 (0.16)	0.72 (0.15)
DBP_{Uni} (s)	0.62 (0.17)	0.55 (0.14)	0.5 (0.12)	0.58 (0.17)	0.55 (0.13)	0.49 (0.13)
CV DBP	0.33 (0.23)	0.19 (0.23)	0.15 (0.10)	0.20 (0.20)	0.13 (0.09)	0.07 (0.05)

DLO = Duraiton Lid Opening ; DBP = Duration Button Press; s = seconds, CV = Coefficient of Variation, Uni = Unimanual Task Execution; DC = Dominant Hand Condition, NC = Non – Dominant Hand Condition

Table 3 Mean (SD) of absolute values and CV of variables reflecting temporal cooperation according to condition and different age bands

	DC			NC		
	Young Children	Older Children	Ado-lescents	Young Children	Older Children	Ado-lescents
MO (%)	42.6 (17.3)	60.1 (19.7)	59.3 (12.0)	50.8 (24.9)	55.9 (15.6)	60.6 (21.5)
CV MO	0.17 (0.09)	0.19 (0.12)	0.14 (0.08)	0.09 (0.09)	0.13 (0.06)	0.08 (0.04)
GS (%)	87.5 (8.6)	92.8 (8.9)	93.4 (7)	92.7 (7.3)	93.7 (5.3)	94.4 (7.3)
CV GS	0.09 (0.09)	0.08 (0.04)	0.05 (0.03)	0.07 (0.04)	0.05 (0.03)	0.06 (0.06)

MO = Movement Overlap; GS = Goal Synchronisation; CV = Coefficient of Variation; % = Values expressed as a percentage of Total Task Duration, DC = Dominant Hand Condition, NC = Non – Dominant Hand Condition

Table 4 Mean (SD) of absolute values and CV of variables reflecting trajectories of the button press movement during uni- and bimanual task execution according to condition and different age bands

	DC			NC		
	Young Children	Older Children	Ado-lescents	Young Children	Older Children	Ado-lescents
PL_{Uni} (m)	0.49 (0.10)	0.45 (0.05)	0.42 (0.03)	0.49 (0.06)	0.47 (0.06)	0.42 (0.04)
ZC	6.80 (2.81)	4.39 (1.19)	3.78 (0.69)	5.83 (2.05)	3.75 (0.78)	3.72 (0.78)
ZC_{Uni}	3.13 (1.76)	2.54 (1.27)	2.06 (0.53)	2.87 (1.25)	2.39 (1.10)	2.22 (1.06)
CV ZC	0.42 (0.21)	0.35 (0.18)	0.49 (0.19)	0.31 (0.14)	0.43 (0.16)	0.40 (0.14)

PL = Path Length, ZC = Zero Crossings of Acceleration Curve, CV = Coefficient of Variation, Uni = Unimanual Task Execution, BP = Button Press, DC = Dominant Hand Condition, NC = Non – Dominant Hand Condition