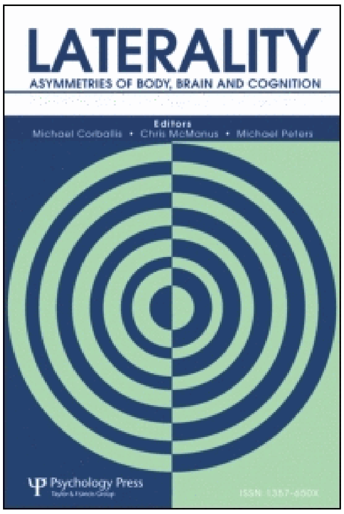

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Brain lateralisation and motor learning: Selective effects of dominant and non-dominant hand practice on the early acquisition of throwing skills

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Brain lateralisation and motor learning: Selective effects of dominant and non-dominant hand practice on the early acquisition of throwing skills

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Findings from neurosciences indicate that the two brain hemispheres are specialised for the processing of distinct movement features. How this knowledge can be useful in motor learning remains unclear. Two experiments were conducted to investigate the influence of initial practice with the dominant vs non-dominant hand on the acquisition of novel throwing skills. Within a transfer design two groups practised a novel motor task with the same amount of practice on each hand, but in opposite hand-order. In Experiment 1, participants acquired the position throw in basketball, which places high demands on throwing accuracy. Participants practising this task with their non-dominant hand first, before changing to the dominant hand, showed better skill acquisition than participants practising in opposite order. In Experiment 2 participants learned the overarm throw in team handball, which requires great throwing strength. Participants initially practising with their dominant hand benefited more from practice than participants beginning with their non-dominant hand. These results indicate that spatial accuracy tasks are learned better after initial practice with the non-dominant hand, whereas initial practice with the dominant hand is more efficient for maximum force production tasks. The effects are discussed in terms of brain lateralisation and bilateral practice schedules.

Keywords: Motor learning; Intermanual transfer; Hemispheric specialisation; Throwing skills.

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Previous studies have shown that practising complex sport skills on both sides of the body benefits performance not only with the non-dominant limb, but also with the dominant limb (e.g., Haaland & Hoff, 2003; Maurer, 2005; Puretz, 1983; Teixeira, Silva & Carvalho, 2003). For example, Haaland and Hoff (2003) examined two groups of experienced soccer players in three soccer-specific tests (dribbling, volley goal shot, and passing against a mini goal) after they had practised over several weeks using either only their dominant leg or their non-dominant leg. As would be expected, the non-dominant leg group performed better across all tasks when tested with the non-dominant leg after the training period. Not expected, however, was the finding that the non-dominant leg group also showed greater performance improvements when tested on their dominant leg (when compared to the dominant leg group). Thus non-dominant leg training led to a general improvement of skill performance on both sides of the body, even in experienced soccer players. These results were at least partially confirmed in another study by Teixeira et al. (2003), who found a similar reduction of lateral asymmetries for a soccer dribbling task after non-dominant leg practice (but no reduction in two other tasks, kicking for force and kicking for accuracy). Most interestingly, these effects of dominant and non-dominant limb practice have been observed to even affect sports that are only played on one side, such as table tennis (Maurer, 2005).

The ability to perform particular skills with both sides has often been related to intermanual transfer effects that arise after dominant and non-dominant limb practice and reflect the exchange of specific movement components between the two limbs. Because these movement components transfer with different magnitude and in different direction (e.g., Carson, 1989; Teixeira, 2000), contralateral transfer effects are highly task specific and are mainly asymmetric (Magill, 2001). For example, a number of studies on simple motor actions (e.g., reaching and pointing tasks) suggest stronger intermanual transfer of movement dynamics (i.e., the regulation of movement forces) from the dominant (right) arm, to the non-dominant (left) arm (Criscimagna-Hemminger, Donchin, Gazzaniga, & Shadmehr, 2003; Farthing, Chilibeck, & Binsted, 2005; Teixeira & Caminha, 2003). Such differences in the direction of intermanual transfer have important practical implications when it comes to the scheduling of early motor learning processes. With regard to this, Richard Magill stated that "if asymmetric transfer predominated, the therapist, instructor, or coach would decide to have a person always train with one limb before training with the other; [...] if symmetric transfer predominated, it would not make any difference which limb the person trained with first" (Magill, 2001, p. 213). Following this notion in two recent studies we investigated the optimal selection of the initial practice side by adding another period of opposite limb training after a period of dominant or non-dominant limb practice (Senff & Weigelt, 2011;

Stöckel, Weigelt & Krug, in press). Stöckel et al. (in press) had two groups of adolescent participants practise a basketball dribbling task in opposite training schedules, starting either with the dominant or the non-dominant hand (with the amount of practice with each hand counterbalanced). The results of this study demonstrated improved bilateral performance (i.e., faster dribbling times with the dominant and the non-dominant hand) for the training group that started to learn the dribbling task with their non-dominant hand. Similar results were obtained by Senff and Weigelt (2011), who asked children to slide cent coins from a starting position into a target on the opposite side of a table. Those children who practised this task initially with the non-dominant hand performed better with both hands afterwards, displaying greater sliding accuracy on their dominant and on their non-dominant side. Hence the results of these two studies revealed *sequential effects* on the acquisition of complex motor skills, such that the initial side practised influences how well a particular skill will be learned on both sides.

These sequential effects on skill acquisition can be explained with the notion of task-specific transfer of different movement components (Carson, 1989; Teixeira, 2000), in this case with the stronger transfer of visual-spatial task components from the non-dominant to the dominant side of the body. This notion receives further support from new findings in neuroscience research, which indicate the specialised processing of distinct movement components in the two brain hemispheres (Birbaumer, 2007; Gazzaniga, Ivry, & Mangun, 1998; Serrien, Ivry, & Swinnen, 2006). Here the following picture in terms of hemispheric specialisation and task control emerges: While the left hemisphere is primarily responsible for the temporal and sequential control of movements (i.e., the control of movement trajectories) and the regulation of dynamic aspects (i.e., fine-force control), the spatial orientation and coordination of actions (i.e., the control of final positions and targeted precision) are processed in the right hemisphere (see Serrien et al., 2006, for an overview). Such a general model of brain asymmetries and hemispheric specialisation suggests that "both hemispheres are likely to be involved in the performance of any complex task, but with each contributing in their specialised manner" (Gazzaniga et al., 1998, p. 369). It is further in line with the dynamic dominance hypothesis of motor control (cf. Sainburg, 2002; Sainburg & Eckhardt, 2005), which assumes that voluntary movements are controlled by two specialised brain hemisphere/limb systems, each stabilising different features of task performance (Sainburg & Kalakanis, 2000; Wang & Sainburg, 2007). In this regard, a greater proficiency of the left-brain/right-hand system has been demonstrated in the control of trajectory dynamics, while the right-brain/left-hand system appears to better specify the final position of a movement (e.g., Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis 2000; Sainburg

& Wang, 2002; Wang & Sainburg, 2004). How such theorising can be applied to the acquisition of complex sport skills is of further interest to the present investigation. In particular, the optimal selection of the initial practice side should be a strong criterion for how to schedule early skill acquisition. While in our previous studies (Senff & Weigelt, 2011; Stöckel et al., in press) evidence was provided that certain tasks are learned better after initial non-dominant, left-hand practice, the present study investigated task-specific hand-order effects in terms of hemispheric specialisation and motor transfer to distinguish tasks being in favour for initial right-hand practice from tasks that are better learned after initial left-hand practice.

To pursue this issue we conducted two experiments on the acquisition of two different throwing tasks in schoolchildren. We used a "representative design" (Brunswik, 1956), where the skills were practised during otherwise realistic training sessions. Both experiments utilised a fully crossed transfer design, such that two groups practised the throwing task with the dominant and non-dominant hand for an equal amount of time, but in opposite hand-order. In Experiment 1 participants learned the position throw in basketball. This skill places high demands on throwing accuracy and therefore requires the processing of visual-spatial information. In Experiment 2 participants acquired the overarm throw in team handball. This skill emphasises high release velocities and therefore, requires the control of movement dynamics. The specific prediction for Experiment 1 was that if the previously reported sequential effects for tasks mainly requiring the processing of visual-spatial information (Stöckel et al., in press; Senff & Weigelt, 2011) extend to the position throw, greater performance improvements should be found for the group starting to practice the task with their non-dominant hand. For Experiment 2 it was predicted that if the pattern of contralateral transfer found for simple motor tasks (Criscimagna-Hemminger et al., 2003; Farthing et al., 2005; Teixeira & Caminha, 2003) extends to more complex tasks, better skill acquisition should be observed for the group beginning to learn the overarm throw with their dominant hand.

EXPERIMENT 1

Method

Participants. A total of 16 children (14 boys and 2 girls) between 11 and 14 years (age: 12.2 ± 0.8 years) from a German grammar school volunteered in this experiment. All of the children were right-handed. The handedness of all children was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971) before the study, and none of the children had prior experience with the task or played in a basketball team outside school. The testing and practice sessions were arranged during extracurricular activity after school. Informed consent of children's parents was obtained prior to participation in the experiment. The research was approved by the local school authorities and the institutional review board.

Probing task. Participants performed in a test on throwing accuracy, which required them to repetitively throw a basketball into a vertical target circle over a period of 30 seconds (i.e., continuously shooting the ball during the period, being as precise as possible). Participants were asked to only use the technique of the basketball position throw (cf. Vancil, 1996) to perform the test. Variations of the movement pattern were only allowed as long as the basketball position throw was clearly identifiable. Otherwise they were informed about the wrong technique immediately and the throw was not counted. The technique/movement pattern of the position throw was demonstrated to all participants by the experimenter before the first testing session. During the demonstration the experimenter performed the test with the dominant and the non-dominant hand, respectively. The vertical target was placed at a height of 215 cm on the side wall of the gymnasium and consisted of three concentric circles (see Figure 1). The smallest circle was 45 cm in diameter, the middle circle was 90 cm, and the largest circle was 135 cm. For a better orientation, a rectangle of 60 cm by 60 cm demarcated a foot area on the floor and participants were advised to keep their feet within this area during the test. The task was executed best when participants threw the ball in a manner, which enabled them to catch the back-bouncing ball easily and without leaving the foot area that in turn allowed them to quickly

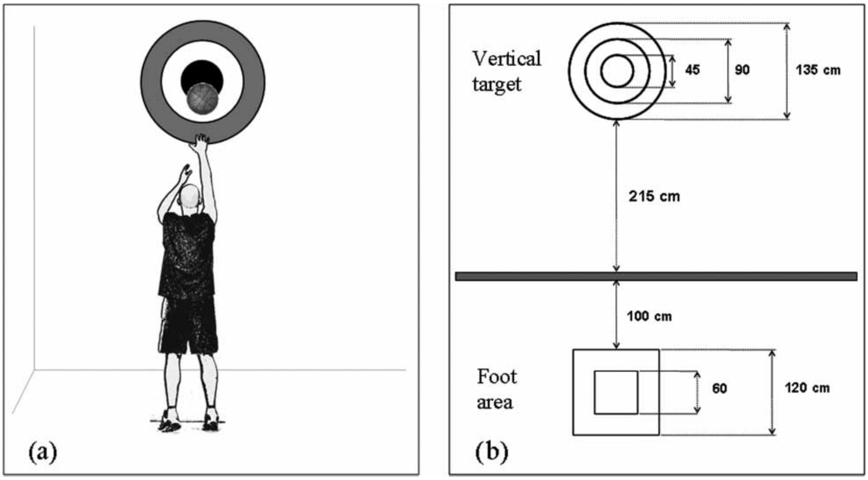

Figure 1. Test on throwing accuracy. (a) Drawing of the position throw with the right hand, (b) Depiction of the task set-up (1:87).

continue with the next throw (and so on). This was ensured when participants continuously hit the centre of the target as precisely as possible. Thus high task performance required the efficient processing of visual-spatial information. The Probing task was always conducted with the dominant hand and the non-dominant hand separately (order counter-balanced across all children). Also, during a modified version of the test, children were asked to alternate between their hands after the retention test (i.e., *intra-task transfer*). The vertical target was replaced by a regular basketball set-up where participants were required to place the ball through a 305-cm high hoop from a distance of 300 cm. The basketball used was of official size, approximately 75 cm in circumference, and with a weight of approximately 600 g.

Design and procedure. All children participated in a pre-test, before they were equally distributed to one of the two experimental groups (according to their pre-test performance). That is, pre-test results were transformed to a rank order from low to high values (averaged over both hands) and all participants on an odd rank were assigned to one group and participants on an even rank were assigned to the other group. In the following acquisition phase (practice sessions) participants practised basketball in their respective group under one of the two order-of-practice schedules. A total of eight practice sessions were administered over a period of 4 weeks. One group of participants used only their dominant hand for sessions 1–4 and then switched to their non-dominant hand for sessions 5–8. This group is referred to as *dominant-to-non-dominant group* (D-ND). The other group practised in the opposite order and is referred to as *non-dominant-to-dominant group* (ND-D). Each session lasted for 45 minutes and followed a methodological procedure commonly used by practitioners to teach children's basketball (e.g., Mondoni, 2000; Vancil, 1996). The practice sessions included different warm-up exercises, ball-handling routines, different drills, and various forms of game play to improve throwing accuracy (using the part–whole method). The main objective during training was to improve children's ball-handling skills in terms of throwing and catching. Thus, during the practice sessions, participants learned accurate throwing and receiving using the technique of the basketball position throw, on which participants were tested before and after the acquisition phase, stepwise following methodological guidelines (e.g., from easy to more difficult, from simple elements of the movement to the whole, complex skill). This training procedure followed the usual approaches to teaching novel skills in sports. For example, they practised ball-handling basics (e.g., wall drill, tap drill, finger flips, catch and throw) and throwing basics on the spot with varying complexity (e.g., throwing with a partner using finger/hand movement, whole arm movement, or whole movement with different distances; throwing to diverse targets at the wall from different distances) to increase movement coordination and throwing accuracy. In each practice session participants threw the ball around 220 to 250 times. Most importantly, the content of practice (i.e., the various drills performed) and the amount of training in each session, as well as the number of repetitions for each exercise was similar for both groups. However, they never practised the standardised accuracy test and no additional data were collected during the acquisition phase. With this procedure, it was possible to use a standardised test to investigate potential sequential effects—which may result from the particular order in which the two hands were practised—during (otherwise) regular basketball training sessions. Changes in performance were examined separately for the dominant and for the non-dominant hand in a post-test (after all sessions were completed), and in a retention test (after 2 weeks without practice). In the retention test children were also asked to perform in a modified version of the test (regular basketball set-up), using both hands in alternation. All participants were instructed to not practise the test in their leisure time. Participant's performance in each testing session was videotaped for further analyses.

Data collection and analyses. In the primary accuracy test condition participants received 3 points when the ball was thrown into the smallest circle, 2 points for the middle circle, and 1 point for the largest circle. No points were awarded when the ball missed the target. If the ball hit the line between two target circles, then either 2.5 points (small/middle circle) or 1.5 points (middle/large circle) were given. In the modified version of the accuracy test (*inter-task transfer*) they received 3 points for scoring without having the ball touch the board or the rim, 2 points for scoring with hitting the board or rim, and 1 point when the ball at least had contact to the rim. To analyse participant's performance all throws were scored for target (or hoop) accuracy by consulting the video sequence of the individual test trial. All points of all throws were added up to receive a sum value of each 30-second test trial. Thus better throwing test performance was reflected in higher sum values, whereas weaker performance was revealed by lower sum values.

Results

In order to test our predictions we examined the throwing scores for participants of both groups in the pre-test, the post-test, and the retention test for both hands separately. The average throwing scores for the dominant and the non-dominant hand are displayed in Table 1. These data were then submitted to a 2 (*Group*: D-ND vs ND-D) × 2 (*Hand*: dominant vs non-dominant) × 3 (*Test*: pre-test vs post-test vs retention test) analysis of variance (ANOVA) with repeated measures on the last two factors. The

TABLE 1
Average throwing scores (in points) in the test on throwing accuracy for the dominant and the non-dominant hand of both groups in the pre-test, the post-test, and the retention test

	D-ND group		*ND-D group*	
Test	*dominant hand*	*non-dominant hand*	*dominant hand*	*non-dominant hand*
pre-test	51.06 (6.42)	37.13 (8.73)	50.31 (4.79)	37.00 (8.49)
post-test	52.13 (7.58)	39.88 (9.04)	57.75 (6.32)	44.94 (9.41)
retention test	51.25 (6.05)	37.94 (9.31)	54.63 (5.11)	41.50 (6.64)

Note: Standard deviations are in parentheses.

factor Group was tested between participants. The three-way ANOVA was used to analyse trials only conducted with one hand (primary accuracy test conditions in the pre-test, post-test, and retention test).

Primary accuracy test. Most importantly, the analysis of the one-hand throwing conditions yielded a significant *Group × Test* interaction, $F(2, 28) = 3.56, p < .05, \eta^2 = .20$. Post hoc *t*-tests found the differences between the two groups to be significant for the post-test, $t(14) = 2.52; p < .05$; *Cohens* $d = 0.77$, and the retention test, $t(14) = 2.14; p < .05$; *Cohens* $d = 0.72$, indicating higher improvements in throwing accuracy of the ND-D group. The average throwing scores of the D-ND group improved from pre-test to post-test by 1.91 points and from pre-test to retention test only by 0.5 points. By contrast, the improvement for the ND-D group was higher, with 7.69 points from pre-test to post-test and 4.41 points from pre-test to retention test. These performance differences between the two groups were obtained similarly for the non-dominant and the dominant hand, which can be inferred from the absence of an interaction effect of the factor Hand with any other factor. There was, however, a main effect of the factor *Hand*, $F(1, 14) = 50.48, p < .001, \eta^2 = .78$, showing that participants performed better with their dominant, right hand (52.85 points) than with their non-dominant, left hand (39.73 points).

To ensure that improvements resulted from an increased throwing accuracy and not from a greater number of throws during the 30-second period, the same three-way ANOVA was utilised again, but with the total number of throws as dependent variable. Differences were found neither between tests nor between groups. The total number of throws during the 30-second period ranged between 19 and 23 throws for all participants. Thus higher scores of the ND-D group in post-test and retention test can be ascribed to a higher throwing accuracy of that group, i.e., a more efficient acquisition of the task after initial non-dominant hand practice.

Modified accuracy test. The averaged throwing scores were 23.56 points for the D-ND group and 26.63 points for the ND-D group. A one-way ANOVA was calculated and the difference of 3.07 points in throwing accuracy between the two groups proved to be significant, $F(1, 14) = 4.73$, $p < .05$, $\eta^2 = .25$. This shows that the ND-D group transferred the previously learned throwing skill better to the game-like situation, i.e., throwing at the regular basketball hoop.

Discussion

The results of Experiment 1 support the notion of sequential effects on skill acquisition after practice with the dominant and non-dominant hand. Task-specific transfer was found in favour of the group that started to practise the skill with the specialised hemisphere/limb system (left hand/right hemisphere system) for this task. According to the general model of hemispheric lateralisation and task control, the two brain hemispheres are responsible for the specialised processing of different movement components (Birbaumer, 2007; Gazzaniga et al., 1998; Serrien et al., 2006). In the accuracy test, better task performance resulted from higher target precision (i.e., repetitively bouncing the ball into the smallest target circle), which emphasised the efficient integration of visual-spatial information. It can therefore be assumed that the right hemisphere was the dominant brain side for the processing of the essential components in the throwing skill under investigation in Experiment 1 (position throw in basketball). Thus the ND-D group benefited from the early involvement of the specialised brain hemisphere/limb system during the acquisition phase. This result is in line with a number of recent studies, which similarly employed a fully crossed transfer design and focused on tasks with high demands on the integration of visual-spatial information (Senff & Weigelt, 2011; Stöckel et al., in press).

The generality of sequential effects after dominant and non-dominant practice within fully crossed transfer designs is further tested in Experiment 2. We ask the question if such differences in skill acquisition after a sequential practice schedule will also be present for a throwing task, which emphasises a different task component, namely high release velocities during forceful throwing. To this end, two groups of children learned the overarm throw in team handball under one of two opposite practice schedules. If the specific transfer pattern reported in previous studies on simple motor tasks (Criscimagna-Hemminger et al., 2003; Farthing et al., 2005; Teixeira & Caminha, 2003), demonstrating larger transfer of movement dynamics (force component) from the dominant to the non-dominant arm, extends to the complex task under investigation in Experiment 2 (overarm throw), then children practising the skill with the dominant hand first should show a better acquisition of the task than children starting with their non-dominant hand. To further allude to the specific role that transfer plays on skill acquisition, two types of transfer were examined: Direct transfer signifies performance benefits of the untrained limb after opposite limb practice, whereas indirect transfer resembles the positive influence of having previously practised the task with one limb on the rate of acquisition of this task with the opposite limb.

EXPERIMENT 2

Method

Participants. A total of 16 children (8 girls and 8 boys) from the 5th and 6th grade, ages 9 to 13 years old ($M = 11.7 \pm 1.9$ years) from a German middle school participated in this study. By the standards of the Edinburgh Handedness Inventory (Oldfield, 1971) all children were identified to be right-handed. All testing and practice sessions were arranged during extracurricular activity after school. None of the children had prior experiences with playing team handball. Informed consent of the children's parents was obtained prior to participation in the experiment. The research was approved by the local school authorities and the institutional review board. None of the children participated in Experiment 1.

Apparatus and probing task. To standardise measurements of the skill tested, a mobile linkage ergometer was used to perform overarm throws while pulling on a rope against a predefined low resistance (through a drum brake generating a load of approximately 300 g). The effort spent was comparable to throwing an official size handball. As shown in Figure 2, participants stood facing away from the ergometer and holding the rope at a

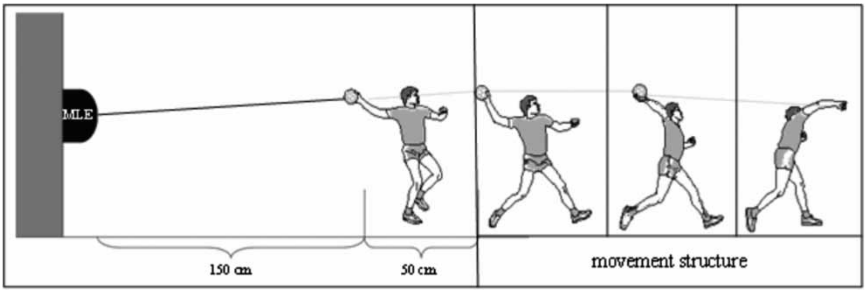

Figure 2. Test on throwing strength at the mobil linkage ergometer (MLE). Depicted is the experimental set-up for the overarm throwing task (left side) and the required movement technique (right side). Adapted with kind permission of BLV publisher, from Kolodziej (2007).

distance of 150 cm. The rope's end was fixated on the ergometer at participants' face level. The hand tested held the rope at the handle using a force grip (cf. Keisker, Hepp-Reymond, Blickenstorfer, Meyer, & Kollias, 2009), which is used similarly—although with a wider aperture—when throwing an official size handball. Participants were told to pull upon the rope as powerfully as possible for a total of six trials (start pulling and continue until after the sixth trial) using the technique of the overarm throw in handball. A start signal was given by the experimenter. The aim of the task was to pull the rope in a way that maximum force (as signified by maximum release velocity) was produced in the final part of the pulling action, which was completed when the throwing arm was fully extended in the end of the motion. From the endpoint the arm had to be slowly returned to initial position for the next pulling action. Participant's throwing performance was assessed by maximum release velocity, i.e., maximum instantaneous velocity near the endpoint (in m/s).

Design and procedure. The fully crossed transfer design was similar to the one used in Experiment 1, with the only difference being the inclusion of an additional intermediate test after the first acquisition phase, when participants changed their practice hand. This test was included to test for intermanual transfer to the untrained limb. All participants were equally distributed to one of two groups after a pre-test in the same manner as described for Experiment 1. Then both groups participated in regular team handball practice sessions under one of two treatment conditions: (1) Participants practised with their dominant hand for the first half of the acquisition phase and then switched to their non-dominant hand for the second half (*dominant-to-non-dominant group* [D-ND]); or (2) Participants started with their non-dominant hand for the first half of the acquisition phase and then switched to their dominant hand for the second half (*non-dominant-to-dominant group* [ND-D]). The experimental design included the *pre-test*, the *acquisition phase* with eight practice sessions (over 4 weeks), the *intermediate test* (before the change of hands) to test for direct and indirect intermanual transfer, the *post-test* (after the acquisition phase was completed), and the *retention test* (after 1 week without practice). All tests were conducted separately for the dominant and the non-dominant hand (order counterbalanced across participants). The whole study lasted for 6 weeks. All participants were instructed to not to practise the test in their leisure time.

The testing and training sessions were arranged during extracurricular activity classes in a gymnasium. Each session lasted for 45 minutes and followed a methodological procedure commonly used by practitioners to teach children handball throws (cf. van den Tillar, 2004). The training programme focused on the acquisition of the basic skill and on a programme to improve throwing strength and velocity by optimising the dynamic parameters of the overarm throw (van den Tillar, 2004). Participants learned powerful throwing, which was tested in the probing task, stepwise following methodological guidelines (e.g., from easy to more difficult, from simple elements of the movement to the whole, complex skill). For example, they practised ball-handling basics, throwing basics on the spot with varying distances and balls (e.g., powerful overarm throws with a partner with different balls or to a target at the wall from different distances), and throwing with maximum effort (e.g., to the wall, mats or other targets) to enhance throwing strength and movement coordination. In each practice session participants threw the ball around 250 to 270 times using the overarm throw. Again, all contents of practice (i.e., the various drills performed) and the amount of training in each session, as well as the number of repetitions for each exercise were similar for both groups.

Data collection and analyses. For the examination of participant's throwing strength, the velocities for pulling the rope of the mobile linkage ergometer were continuously recorded on a PC via a serial digital interface. For later analysis, only the maximum instantaneous velocity at the end of each trial was stored. The relevant parameter is therefore called *maximum release velocity*, because participants achieved highest velocities at the end of the movement with the pulling arm fully extended—a position that is equal to the ball release position in overarm throws. Individual throwing performance was calculated from the performance of the third, fourth, and fifth trial to specify average maximum release velocity (in m/s) in one series of six overarm throws. Thus, better throwing test performance was reflected in higher averaged maximum release velocities. Trials 1 and 2 were conducted for movement initiation and the last trial was used to slow down the movement.

Results

The average maximum release velocities for the dominant and the non-dominant hand are displayed in Table 2. This data was submitted to a 2 (*Group*: D-ND vs ND-D) × 2 (*Hand*: dominant vs non-dominant) × 3 (*Test*: pre-test vs. post-test vs. retention test) analysis of variance (ANOVA) with repeated measures on the last two factors. The factor Group was tested between participants. To examine for potential effects of direct intermanual transfer, separate *t*-Tests were performed based on the data of the intermediate test for participant's performance (or following the acquisition process) with the untrained limb.

TABLE 2

Average release velocities (in ms) in the test on throwing strength for the dominant and the non-dominant hand of both groups in the pre-test, the post-test, and the retention test

	D-ND group		*ND-D group*	
Test	*dominant hand*	*non-dominant hand*	*dominant hand*	*non-dominant hand*
pre-test	4.76 (1.53)	4.22 (0.99)	4.90 (1.05)	4.27 (0.56)
intermediate-test	5.51 (2.34)	4.31 (1.19)	4.68 (1.02)	4.35 (0.60)
post-test	6.01 (2.04)	4.79 (1.16)	5.09 (1.16)	4.38 (0.72)
retention test	5.79 (1.94)	5.05 (1.29)	5.33 (0.91)	4.66 (0.61)

Note: Standard deviations are in brackets.

Throwing strength. Data analysis of participant's throwing strength yielded a significant *Group* × *Test* interaction, $F(2, 28) = 3.27$, $p < .05$, $\eta^2 = .18$. Again, post hoc *t*-tests found the differences between the two groups to be significant for the post-test, $t(14) = 2.03$; $p < .05$; *Cohens d* = 0.57, and the retention test, $t(14) = 1.69$; $p < .05$; *Cohens d* = 0.41, one-tailed, indicating higher improvements of the D-ND group. The averaged maximum release velocity of the ND-D group improved from pre-test to post-test only by 0.15 m/s and from pre-test to retention test by 0.40 m/s. The improvement for the D-ND group was with 0.91 m/s from pre-test to post-test and 0.93 m/s from pre-test to retention test significantly higher. The main effect for *Hand* was also significant, $F(1, 14) = 25.44$, $p < .001$, $\eta^2 = .65$, showing that participants achieved higher maximum release velocities with their dominant, right hand (5.31 m/s) than with their non-dominant, left hand (4.56 m/s), as would be expected.

Intermanual transfer. The average maximum release velocities for the dominant and the non-dominant hand of both groups in the intermediate test are further displayed in Table 2. The present fully crossed transfer design is appropriate to identify two kinds of intermanual transfer: First, the untrained hand can directly benefit from practice with the opposite hand. This was analysed with a paired-samples *t*-test for the untrained hand between pre-test and intermediate test. The values in Table 2 illustrate that neither the untrained non-dominant hand in the D-ND group (+ 0.09 m/s), nor the untrained dominant hand in the ND-D group (–0.22 m/s) benefited directly from opposite hand training. The absence of direct intermanual transfer was statistically confirmed by a single paired-samples *t*-test, $t(14) = 1.01$, $p > .05$. Second, initial practice with one hand can indirectly affect the subsequent acquisition process with the opposite hand. Therefore, changes in performance through practice as initial hand-in-practice (from pre-test to intermediate test) or as second hand-in-practice (from intermediate test to post-test) were compared using a single independent samples *t*-test, which proved to be significant, $t(14) = 2.11$; $p < .05$; *Cohens* $d = 1.23$, for the non-dominant hand. Accordingly, the dominant hand improved by 15.8% when acting as first hand-in-practice, but only improved by 8.8% as second hand-in-practice (i.e., after initial non-dominant hand practice). This shows that there are no indirect effects of initial non-dominant hand training on the following dominant hand practice. In contrast, the non-dominant hand only improved by 1.9% when acting as first hand-in-practice, but improved by 11.1% as second hand-in-practice (i.e., after initial dominant hand practice). This shows that the non-dominant hand (as second hand-in-practice) indirectly benefited from initial dominant hand practice.

Discussion

The notion of sequential effects on the acquisition of complex motor skills is further supported by the results of Experiment 2. As these results show, starting to practise with the dominant hand benefited the acquisition of the throwing task (overarm throw), as compared to beginning with the non-dominant hand. More specifically, the D-ND group improved their throwing strength after the pre-test with both hands by 19.9% in the post-test and by 20.7% in the retention test. However, the improvement of the ND-D group was considerably lower, with 4.3% in the post-test and 10.3% in the retention test. This pattern of results can be explained by the specific task requirements, which emphasised the generation of high movement forces (as signified by release velocities). According to the dynamic dominance hypothesis, dynamic aspects of a movement are better controlled by the left-hemisphere/right-hand system (Sainburg, 2002; Sainburg & Eckhardt, 2005). Therefore, the D-ND group may have benefited from initial practice with the dominant hand, because the important movement components were controlled by the specialised hemisphere/limb system, whereas initial practice with the non-dominant hand did not support skill acquisition in the ND-D group.

The results of the intermediate test are two-fold when it comes to the optimal direction of intermanual transfer for the acquisition of the overarm throw. First, there were no differences in the amount of direct intermanual transfer between the two limbs. So far, this is not in line with previous studies, which found direct intermanual transfer from the dominant to the non-dominant arm for tasks emphasising the control of movement dynamics (e.g., Farthing et al., 2005; Teixeira, 2000; Teixeira & Caminha, 2003). Second, the sequence of dominant vs non-dominant hand training took an indirect effect on the second phase of the practice schedule. That is, performance with the non-dominant hand improved significantly more strongly during training in the second phase, when the skill was practised with the dominant hand first. Interestingly, the dominant hand did not improve as strongly in the second phase, when the non-dominant hand was initially practised. In fact the untrained, dominant hand of the ND-D group even revealed a performance decrement during the first phase (by −4.5%), as compared to their pre-test results.

GENERAL DISCUSSION

The results of the present study are in line with two previous studies reporting sequential effects on the acquisition of complex (sport) motor skills (Senff & Weigelt, 2011; Stöckel et al., in press). Specifically, it was found that initial practice with the non-dominant, left hand benefited the acquisition of the position throw (basketball skill) in Experiment 1, whereas the overarm throw (team handball skill) in Experiment 2 was learned better after initial practice with the dominant, right hand. Importantly, these task-specific sequential effects equally affected the acquisition of the skill on both hands, the dominant and non-dominant hand respectively. Below we further discuss these results in the context of the general model of hemispheric lateralisation and provide an extended model on the role of specialised information processing during skill acquisition with the dominant and non-dominant limb.

An extended model of the specialised processing and transfer of information

We argue that the present results can be attributed to the specialised processing of different movement features in the early learning process. Our argumentation is based on the general model of hemispheric lateralisation and considers differences in hemispheric specialisation (cf. Sainburg, 2002; *dynamic dominance hypothesis*; for an overview see also Serrien et al., 2006). Accordingly, the left hemisphere is primarily responsible for the sequential control of movement patterns (i.e., trajectory coordination) and the regulation of movement dynamics (i.e., force control). However, visual-spatial aspects of movements (i.e., control of target position) are processed in the right hemisphere. Taking this model and the present findings into account, it seems reasonable to assume that initially “practising” the specialised right-hand/left-hemisphere system results in a better acquisition of those motor skills, which emphasise the generation of movement forces and thus, the control of movement dynamics. On the other hand, "practising" the specialised left-hand/right-hemisphere system should result in a better acquisition of skills, which require high visual-spatial coordination and accuracy. This may be due to establishing a better representation of a particular movement in the hemisphere that is specialised for the processing of specific movement components or task features. A similar argumentation has also been provided by other authors, who concluded from their studies that each hemisphere/limb system is "specialised for stabilising different features of task performance" (e.g., Wang & Sainburg, 2007, p. 569; Wang & Sainburg, 2004).

The latter theorising helped to explain a number of intermanual transfer effects observed for simple motor actions, but it fails to fully account for the distinct patterns of sequential effects on the acquisition of complex skills in the two present experiments. Rather, these sequential effects can be explained by better skill representations after initial practice with the specialised hemisphere/limb system, and not with practising the specialised system per se. This places a strong emphasis on the scheduling of dominant vs non-dominant practice. It is further assumed that the stored movement components or task features of one hemisphere are used by the other, contralateral hemisphere via the neuronal connections of the corpus callosum (Bloom & Hynd, 2005; Perez, Wise, Willingham, & Cohen, 2007). This may result in a better access/transfer of information of the untrained limb after practising a skill with the specialised hemisphere/limb system. On the other hand, initial practice with the non-specialised hemisphere/limb system will generate a weaker representation of the movement. Moreover, the results of Experiment 2 suggest that this weaker representation may interfere with the acquisition when the skill is later on practised with the specialised system. This notion is similar to the argumentation of Wang and Sainburg (2004). They suggested that, while adapting to novel limb dynamics, dominant arm learning—as compared to non-dominant arm practice—leads to a more accurate model/neural representation, which can be accessed/utilised by the non-dominant arm controller. Consistent with our assumption they explained their findings with differential proficiencies of the arm controllers in developing internal models of distinct features of a movement.

Figure 3 illustrates the model of *specialised information processing and transfer* for the acquisition of a complex task with high demand on visual-spatial coordination, such as for the position throw in basketball, for which the right hemisphere is specialised to process the relevant task features. Up to now, the approach only allows us to derive predictions for right-handers, because studies investigating the optimal initial practice side and intermanual transfer in left-handers are missing.

The aforementioned model extends Parlow and Kinsbourne's *cross activation model* (1989) by the perspective of the dynamics of hemispheric

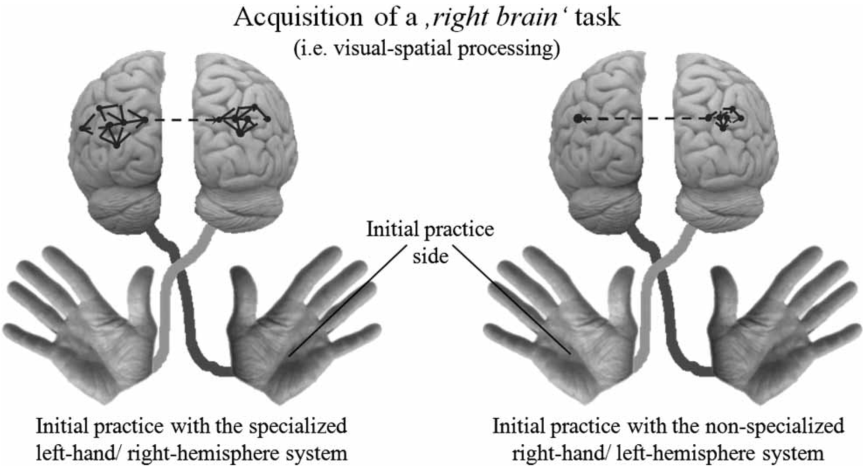

Figure 3. Model of the specialised processing and transfer of information. Approach of interhemispheric communication in early motor skill acquisition illustrated for tasks with a high demand on visual-spatial processing, for which the right brain hemisphere is specialised. The patterns of black dots and lines illustrate the activation of neuronal networks in the hemisphere directly controlling the trained limb, as well as the co-activation in the contralateral hemisphere (controlling the untrained limb). The size of the neuronal networks depicted, are thought to represent the quality of stored movement representations. The model suggests beneficial hemispheric interaction and thus, a better acquisition of the skill with both hands, when a task is initially practised with the specialised brain hemisphere/limb system (left side), but limited interaction and thus, weaker skill acquisition, when the non-specialised brain hemisphere/limb system is involved (right side). The opposite pattern of neuronal activation and co-activation with the specialised and non-specialised brain hemisphere would be predicted for tasks that require the control of movement dynamics, such as during the generation of large movement forces.

specialisation (Serrien et al., 2006). The cross activation model states that during initial learning with the dominant arm learned information is stored in the dominant hemisphere and a copy of the acquired information (including a representation of specific task features and movement components) is simultaneously stored in the non-dominant hemisphere. This suggests that only such features of a movement for which the dominant arm (i.e., the right arm in right-handers and the left arm in left-handers) is most proficient will transfer. But what about those movement features for which the non-dominant hemisphere is specialised? Since our data revealed contrary patterns for hand-order effects for the learning of different throwing tasks in right-handers, the cross activation model seems also be valid for tasks/movement components for which the non-dominant, right hemisphere is specialised, when replacing the term *dominant* by *specialised* (i.e., for certain movement features) within Parlow and Kinsbourne's approach. From our findings, we suggest that during initial learning with the specialised brain hemisphere/limb system movement information is primarily processed and stored in the specialised hemisphere and a copy is simultaneously stored in the non-specialised hemisphere. Which brain hemisphere/limb system is specialised for a certain task depends on the task's inherent demands. This point of view receives further support from a broader basis of neuroscientific findings (cf. Birbaumer, 2007; Serrien et al., 2006) and a number of other studies on interlimb transfer and on sequential effects in practice (e.g., Farthing et al., 2005; Haaland & Hoff, 2003; Senff & Weigelt, 2011; Stoddard & Vaid, 1996; Stöckel et al., in press; Teixeira, 2000; Teixeira et al., 2003). A final conclusion about whether a *copy* of the movement representation is in fact stored in the non-dominant/non-specialised hemisphere (albeit, perhaps with lesser quality) or whether the non-specialised hemisphere/limb system has *access* to the information learned with the specialised hemisphere/limb system cannot be reached based on the present data. Therefore, this issue is most relevant to future research, e.g., by using repetitive TMS to disturb learned structures systematically in the two hemispheres.

Implications for the acquisition of complex motor skills

The present results suggest that the optimal initial practice side (e.g., dominant vs non-dominant hand) on which a particular skill should be trained with both hands depends on the specific task features and inherent movement components. This finding can help to optimise practice schedules, as it emphasises the importance of inherent task demands on the selection of the initial side of practice for the acquisition of complex sport skills. Based on these and previous findings from our laboratory (Senff & Weigelt, 2011; Stöckel et al., in press), complex motor skills, which place high demands on the processing of visual-spatial information (e.g., position throws in basketball or playing darts), should be initially taught with the non-dominant, left hand, whereas motor skills, which require the generation of movement dynamics (e.g., throwing long passes in basketball or American Football), should benefit from initial dominant, right-hand practice. Importantly, beginning to practise a particular skill on the optimal initial side will benefit not only the acquisition with the practised limb, but also with the untrained limb. Any reduction of lateral performance asymmetries essentially results in higher bilateral competence of the athlete. Thus, the present findings should be of great interest for teaching skills in a number of sports, which require the flexible coordination of movements on the dominant and non-dominant side, without much decrement in performance. In basketball, for example, the offensive player often does not have the time to switch to his/her dominant side when under pressure from an opponent's defender. Instead, this situation requires the offensive player to dribble or throw the ball with the non-dominant hand. Most importantly, the ability to execute complex skills well on both sides (i.e., a high degree of bilateral competence) provides the player with additional capacity to focus on other aspects of performance, such as tactical decision making.

After all, the non-dominant, left side should be integrated systematically into early skill acquisition in order to benefit from interlimb transfer effects and to avoid lateral performance asymmetries. This is especially important in game sports, where it has been shown that unilateral practice with the dominant limb does not automatically result in better skill acquisition (e.g., Haaland & Hoff, 2003; Maurer, 2005; Stöckel et al., in press; Teixeira et al., 2003). Hence, the present findings should be of particular interest to physical therapists, instructors, and coaches, who are encouraged to revise their practice schedules to enhance motor learning processes and performance improvement.

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