Bachelor thesis
(Supervised by Prof. E. M. Rouiller and Dr T. Wannier)

Relation between hand preference and hand dominance in human: a behavioral study

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Abstract

This study investigates hand preference and hand dominance in human subjects. It was performed on two groups, ten left-handed subjects and ten right-handed subjects. The evaluation of the hand preference was made with a “handedness questionnaire” which gave an evaluation of the laterality for each subject. The hand dominance was evaluated using the modified Brinkman board task specially adapted to human’s hand morphology. The results indicate a strong relation between hand preference and dominance in these experimental conditions. The left-handed subjects were significantly better with their left hand than with their right one. In contrary, the right handers were significantly better with their right hand. Other observations concerning the behavioral data are also presented in this work.
Introduction

Since long ago, the concepts of handedness and laterality are known, but for a large part of the population they just indicate with which hand you hold a pen to write a letter. In fact those concepts cover different neuronal and behavioral aspects.

This work aimed at investigating in the same subjects hand preference and hand dominance. There, hand preference indicates which hand a person will choose “instinctively” to do a specific task without really knowing if he is more efficient with one or with the other hand. In contrast, hand dominance relates to the performance of each hand to execute a particular action. In this case, your dominant hand will be the one with which you perform best a specific task.

In a first part, I will review literature, to clarify the concepts that are important to approach this complex problematic and then I will indicate what are the known relationships between them. In a second part, I will describe a behavioral study of hand dominance using the modified Brinkman board task and an evaluation of the handedness (a more general view of the hand preference including several aspects) with a questionnaire. These data are used to assess whether there is a relationship between hand preference and hand dominance under the experimental conditions used in the present study.

The research group of Prof. E.M. Rouiller has been focused since many years on some aspects of the motor control. For their experiments, they used crab eating monkeys (macaca fascicularis), to evaluate some aspects of the CNS regeneration or reorganization after cortical and spinal lesions at the adult stage. It is also important to have a point of comparison with humans, which can contribute to a better comprehension of this system. This work has not for aim to compare results between human beings and monkeys but more to give an evaluation of the fine manual dexterity of human and to put it in relationship with an other aspect which is the lateralization of the hand in human.
Specific regions of the central nervous system control voluntary and involuntary movements. Those regions are organized in a hierarchical manner and a parallel manner. The hierarchical organization can be seen as consisting of three separated levels. The highest level, which is made by the associative areas of the neocortex and by the basal ganglia, is involved in finding which strategy is better to reach a specific goal. The second level has more to do with the fine control of the movement, it specifies the “parameters of the movement”. The motor cortex and the cerebellum are important component of this level. The lowest level is more involved in the execution of the movements. The brain stem and spinal cord take part in this action which involves their connections to motoneurons or interneurons. This last level is specially implicated in the control of the involuntary movements such as reflexes. Sensory inputs are integrated at all those levels and play an important role in the modulations of the movements by the supraspinal centers.

Figure 1: localisation of the different motor areas in human and macaque without cingulate motor area.
Notice that only the motor cortex and the brain stem have direct connections to the spinal cord. The other parts involved have only indirect access through them.

The motor cortex plays a predominant role in the motor system. It is constituted by the Brodmann’s areas 4 and 6 that are parts of the frontal lobe and located on the pre-central gyrus and sulcus. Their organization in human patients has been put ahead by the neurosurgeon Wilder Penfield who stimulated electrically these cortical areas and obtained the first map of the human motor cortex. His work allowed to recognize that there was a somatotopic organization of motor cortex (a certain field in the motor cortex is connected specifically and with spatial relation to a group of muscles). In 1905 A. Campbell proposed that the area 6 was important for the movements that required more constructions. This theory was confirmed by Penfield. He separated the area 6 in two: the pre-motor area (PMA) and the supplementary motor area.
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(SMA). Those areas have also a somatotopic representation. Moreover there is a 4th motor area: the cingulate motor area which overlaps the area 24 and a part of the area 6 of Brodman.

All these areas have specific properties related to different aspects of motor control. M1 plays an important role in performing simple motor tasks whereas, the premotor areas SMA and PM are involved in more complex motor tasks. They also play a role in planning the movements. In our case, it is interesting to point out the fact that area PMv-r shows a specialization for manipulating objects with the hand. Several other parts of the brain play also important roles in the motor actions such as the cerebellum, basal ganglia or the brainstem. These areas will not be discussed in more detail in this work.

The descending connections between the brain and the spinal cord are made with rubrospinal, reticulospinal, vestibulospinal and corticospinal (CST) tracts. The first three are more involved in the involuntary control of the movements as locomotion or posture but the last one, the corticospinal tract, plays a key role in the voluntary movements. We must keep in mind that these different parts are interconnected, multifunctional and work together to give finally an appropriated movement.

**Corticospinal system**

The motor cortex use a collection of millions of corticospinal neurons (in human) to reach the effector organs (muscles) via the spinal cord. This descending pathway is called the corticospinal pathway or also pyramidal pathway. It is interesting to see that this corticospinal tract (CST) has evolved through the ages and played certainly a key role in the development of the advance motor function by primate contrary to the rubrospinal tract which seems to have less importance in motor control in primates (Phillips, 1971; Kuypers, 1981; Heffner & Masterton, 1975, 1983). The CST is composed of pyramidal neurons. There cell bodies are located in the layer V (Catsman-Berrevoets & Kuypers, 1976; Jones & Wise, 1977) of the different motor
areas (M1 50% (Dum & Strick 1991), PM 10%, SMA 20%, CMA 20%). The CST can be divided into two main sections: the lateral pathway and the ventromedian pathway. These tracts allow a quite direct control of the cortex on spinal motoneurons. The lateral corticospinal track constitute an important component of the motor system. It contains 90% to 95% of the axons of CST projection on the spinal cord. They are mainly coming from the frontal lobe (motor areas), then they descend through the internal capsule and at the level of the pyramidal decussation (in the medulla) they cross the medial line to terminated in the spinal cord on the contralateral side. The ventromedian projection is made of 5% to 10% of the corticospinal axons, it is uncrossed and has an importance in the control of proximal and axial muscles. In opposition, the lateral pathway is more involved in the control of distal muscles (e.g. hand muscles). The CST axons can contact the alpha motoneurons either directly or indirectly via interneurons. The direct CST is also called the corticomotoneuronal projection (CM) (Bernhard & Bohm, 1954). It can be seen has a the second major development of the motor system (Bernhard, Bohm & Petersen, 1953; see Phillips & Porter, 1977). The CM system seems to be a specificity of the primate motor control and they are the support of the fine manual dexterity. Contrary to the indirect CS projections, the CM system seems to take its origin only in M1 and to develop itself post-natal (Edgley, Eyre, Lemon & Miller, 1990) and to reach its maturity at the age of 2 years of life in human (Miller & Ramesh, 1991). The repetitive stimulation of corticospinal neurons in the cortex gave progressively an augmentation of the EPSP in the alpha motoneurons. This increasing of the response and the direct access of the CM system on motoneurons seems to be one aspect of the capacity to move fingers independently by primates as for example in the precision grip (opposition of thumb and index finger).
The precision grip

The precision grip is a specificity of the primate and was define by Hepp-Reymond and Wiesendanger (1972) has a highly developed motor function. It consists in the opposition of two fingers: the thumb and the index and is referred to as the fine manual dexterity. Even if this movement seems very simple, it involves several different muscle of the hand and arm, multi-articular chain, tendons, ligaments. In fact to execute the precision grip you also need to stabilized your upper limbs to be
efficient (Porter and Lemon 1993) and you need the cooperation of many muscles. In the control of the arm muscles the indirect corticospinal neurones play an important role. Effectively they are ending on interneurons in the spinal cord which are themselves connected to several alpha motoneurons and they could control the hand stability during the action by co-activation (smith 1981). ON the other hand, the direct CST (the CM system) is the anatomical support of the skilled hand movements e.g. fine manual dexterity (Bernhard et al. 1953). Notice that the CM system does not play any role in the planing of the hand's movements (Dick et al. 1984; Jeannerod, Michel & Prablanc, 1984). Several studies show that lesions of the CST lead to a loss of capacity to do fine hand actions and specially to perform the precision grip (Twoer 1940,...). Lesions of the primary motor cortex (hand region) has also as consequence a loss of the capacity to perform the precision grip (Rouiller et al. 1998). Another important component to have an efficient control of the motor actions is the sensory input to M1 (Lemon and Porter 1976). Those inputs are critical, as it appears clearly in the cases of neuropathy reported by Rothwell et al. (1982). Effectively, to reach an object or a precise target, visual and tactile sensory informations are very important to allow a coordinated movement (Johansson and Westling 1990).
Laterality & dominance

The general notion of laterality refers to the fact that some people use more their right hand or more their left one. The notion of dominance is well illustrated in musicology where the harmonic is written for the left hand and the melody reserved for the more skilled right hand (e.g. piano). In the nineteenth century, P. Broca discovered a motor speaking center on the left hemisphere. He also put ahead a new theory in which he explained that an entire hemisphere could be dominant. Moreover, he put in relationship the laterality of the speech center (Broca's area) and the handedness (figure 5).
In this section, we will go through the literature dealing with some aspects of handedness, for example its behavioral aspect or the origin of handedness as well as the neurophysiological basis.

<table>
<thead>
<tr>
<th>Handedness</th>
<th>Hemisphere dominance (language)</th>
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<tbody>
<tr>
<td></td>
<td>Left</td>
</tr>
<tr>
<td>Left</td>
<td>70%</td>
</tr>
<tr>
<td>Right</td>
<td>94%</td>
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*Figure 5: Relationship between handedness and hemispherical dominance*

**Development of handedness**

It is now well known that the laterality of the hand appears during childhood. In 1949 G.Hildreth put ahead the evolution of the dextrality (right handedness) in relationship with the age and found that it reaches 92% at the age of two (figure 6). It is worth mentioning that the CM system arrives at maturity at the same age and that both events may be related.
The study of Schutz et al. (1951) showed that the EEG of young children stay the same between the two hemispheres until the age of one.

More recently, a number of articles have tried to give an explanation for the differences of handedness and to find reasons for this lateralization. In 2006, Gurd et al. published a study on handedness in 20 pairs of monozygotic twins. They selected twins showing a different handedness and having grown in the same environmental conditions. After having made several tests, they were able to evaluate the laterality of the two twins. The results are that the right handers are more lateralized than his twin. In 2007, Kastner-Koller et al. published a behavioral study on the hand preference in children between 4 and 6 years old. They also showed that the right handers exhibit a stronger laterality than the left handers. The right handers were also better in the field of visuo-motor skill as well as in visual spatial tasks (cf. Bonoti et al., 2005; Giagazoglu et al., 2001; Karapetsas & Vlachos, 1997; Olsson & Rett, 1989). Those tests of hand preference could be put in relationship with the lateralization, which is really stronger in right handed children than in the others (Gallo, Angioletti & Viviani, 2000). Civardi et al. (1999) used single- and paired-transcranial magnetic stimulation (TMS) to reach the same conclusions.

In an other paper (Hopkins et al. 2007) dealing with the genetic influence on hand
preference in a group of chimpanzees, the researchers found that the genetic factor play a great role in case of stable in utero conditions. Moreover, another study of Hopkins et al. 2000 made also on chimpanzees showed that the handedness of those monkeys is also influenced by the parity (order of the birth) as well as by the age of the mother. Effectively some damage to the brain as well as hormones could influence the handedness. For the last offspring a unbalanced hormonal situation by an old mother could also cause the left-handedness. They conclude also that their results exclude the possibility of socio-economic explanations. Yeo and Gangsted (1993) confirmed that the origin of the human handedness can be related to developmental conditions.

**Neurophysiological approach**

The neurophysiological basis of the handedness are treated in several studies. Hopkins and Pilcher (2007) published a study in which they compare the localization of the motor hand area (knob) by MRI in great apes. The “knob” in the left hemisphere is significantly bigger than on the right. This asymmetry can also be found in humans. Based on data, the authors suggest that this difference of volume of the “knob” may be associated to differences of skills between the hands but the origin of this asymmetry remains unclear.

Following Derakhshan (2005, 2008), we must consider two different kinds of handedness. The behavioral handedness which corresponds to which hand you prefer to use and the neural handedness. He put ahead that we have a dominant motor hemisphere connected to the other one through the corpus callosum (genu). Those hard-wired connections would be unidirectional has it can be seem on the graphics below. The dominant hemisphere (or executive) would have direct control on the contralateral side of the body (dominant hand) but the non-dominant hemisphere has to pass through the corpus callosum to reach the opposite side and finally the effectors (Derakhshan et al. 2004, 2003). In these papers the authors talk
about the decision to execute the movements and not its execution itself. This difference of time is called “interhemispheric transfer time” (IHTT). In their studies they also showed that there is a discordance of 15% to 20% between the behavioral handedness and the neuronal handedness. Fort they this explains some cases of crossed aphasia or crossed non-aphasia.

Figure 7: "(A1) Von Monakow’s classical conception of callosal traffic, depicting homotopical association. (A2 and A3) Depicting the directionality of traffic in neural right (A2) and left (A3) handers. Note the reversal of the directionality of signals in A2 and A3"

Derakhshan et al. also put ahead that the clinical cases of “diaschitic syndrome ” give an irrefutable evidence that those connections are one-way and also excitatory. The confirmation is given by experiments based on transcranial magnetic stimulation (TMS) which abolished the excitatory output from the left motor hemisphere. To recognize the neural handedness, they estimated the reaction time of two symmetrically placed electrodes on effectors and they also recorded the EEG. The results showed a difference of about 100ms between the dominant and non dominant side of the body.
With the EEG data, the authors also concluded that moving the non dominant side of the body implicated both hemispheres. However, moving the dominant side of the body only involved the “major hemisphere”. In cases of callosotomy, the patient lost completely the possibility to choose with which hand he wants to perform the task and the hand not connected became useless because of apraxia.

*Figure 8: " In this patient with right sided alien hand, moving the neurally non-dominant right hand is associated with bi-hemispherical activity at C3 and C4. Moving the dominant left hand, however, is associated with activity at C4 only. The figure also provides an estimate of onset latency of movement potential (NS9) on both sides: 200 ms on the left (C3) and 300 ms on the right (C4), resulting in an estimate of interhemispherical transfer time of 100 ms “*
Materials and methods

Behavioral study

Subjects

The present behavioral study was conducted on twenty persons (students) aged from 19 to 25 years old: ten left handers (five males and five females) and ten right handers (five males and five females). They presented themselves as right or left handers. To improve their motivation, they received 30 CHF each.

Brinkman board task

For this study, we used the Brinkman board as describes by Brinkman and Kuypers (1973) and modified as described by Rouiller et al. (1998). The board has been adapted to human being hand's morphology (Rouiller 2008). This board consists in a wooden board of 580 mm by 285 mm (figure 9). It contains fifty slots of 43 mm long by 22 mm wide and 18 mm deep. Twenty-five slots are oriented vertically and twenty-five slots are oriented horizontally. Each slot allows only to introduce one or possibly two fingers (depending on the finger's sizes). The organization of the fifty slots on the board has been described (Rouiller et al. 1998) and can be seen in figure 8. The board is tilted by 30 % in front of the subject and placed on a table. In each slot we put a bolt (external diameter 18mm, internal diameter 10mm) which are replacing the food pellets that are normally used with the monkeys. The size of a slot is calculated to push the subject to use the precision grip. The goal aimed at using this task is to be able to evaluate a specific aspect of the fine manual dexterity in humans.
Recording of the data

During the test, the number of errors (scraping on the bolt, let it fall) was notice live by the experimenter. For the rest, all the data of all subjects were recorded on video camera and saved on a hard disc to be then analyzed off-line on a computer.
Procedure

Before starting the procedure, the subject has to answer to some questions asked by the experimenter (initials?, age?, sex, sport?, music instrument?). Each subject came only for one unique session.

To perform the task, the subject was asked to place himself in front of the Brinkman board and to seat on a chair placed in the middle of it. The height of the chair and the distance between the subject and the board was adjusted depending on each subject's morphology and determined by the experimenter. With one hand the subject has to keep a small box at the middle of the board in which he will put the bolts. The rules of the task are the following:

1. To perform the task as fast as possible.
2. To take only one bolt each time.
3. To keep the box in the middle of the board.
4. To not throw the bolts into the box.

Those rules were made to normalize the task. The goal was to reduce the large differences of behavior between subjects and to concentrate on the evaluation of the fine manual dexterity.

The subject had to do the task alternatively ten times with his right hand and ten times with his left one (right, left, right, left,...), for more statistical accuracy. The hand with which he started the task was imposed by the experimenter.
**Handedness questionnaire**

In addition to the Brinkman board task, each subject was asked to answer to a questionnaire about handedness. This questionnaire, made by Chris McManus (2009), asks some questions about the life of every day and about the past of handedness of the person (injuries,...). With those answers different scores can be calculated. The questionnaire can be consulted in annex (annex 1) for more information.

**Analysis**

The Brinkman board task was then analyzed using the video recordings for each subject. When the hand of the subject reached the board the chronometer was started. This point is the time point 0”. After 30” and 40” seconds the chronometer was stopped and the number of empty vertical and horizontal counted and recorded on an excel file. This gives two scores for each hand, this step was repeated ten times. It finally give forty scores for each subject.

Concerning the handedness questionnaire the score was calculated as explained by Chris McManus (2009):

“Laterality scores (laterality indices). Score all the items as -1 = Always left, -.5 = Usually left, 0 = Either, +.5 = Usually right and +1 = Always right. For items 4 (dish), 6 (jar) and 9 (potato) a strong right- hander would answer left. These three items should therefore be reverse scored by changing the sign on the values given previously (i.e. +1=Always left, etc.). Having done this then one can obtain several measures:
• Overall laterality score. The average of all eleven items
• Cultural pressure score. Items on which there is strong social/cultural pressure to use the right hand. i.e. 5 (clock), 8 (knife)"

The three last items are not used to calculate a score but are more informative questions which can help to a better understanding of some particular cases.

Statistics

After having collected all the data for all subjects, some statistical tools were used depending on what was tested. Those statistical analyzes were proceed by computer with different softwares (“R”, graphpad, excel). The tools themselves were: t-test matched pairs two simple, U Mann & Whitney test, linear regression test, correlation test (spearmann). The plotting of the different graphics were also made using those softwares. More information about which kind of data were used to give a particular graph or statistical results will be explain in the results section.
Results

**Handedness questionnaire**

All twenty subjects filled the handedness questionnaire.

**Overall laterality score**

On the basis of the handedness questionnaire, score has been calculated for each subject. The scores obtained by all the self announced left-handed subjects were all negative, ranging between -41% to -9% (figure 11, blue bars). On the contrary, scores obtained by the right-handed subjects were all positive, ranging between 36% to 91% (figure 11, red bars). Notice that in general the absolute value of the scores was higher for right handers, an indication that they are more lateralized than the left handers. This was confirmed by a p value < 0.05 (Mann&Whitney U test).

![Figure 11: Overall laterality score for the twenty subjects obtained using the handedness questionnaire (annex 1). Those score are the average of the eleven first items. The scores obtained were transformed in percentages.](image)
Laterality score without social/cultural pressure

In order to clarify whether this difference between the two groups could be due to the effect of cultural or social pressures, the scores were reestablished without taking in account these items with strong cultural or social pressure (items 5 and 8, annex 1). The left handers groups obtained only negative score (figure 12, blue bars), ranging from -16% to -66%. The scores of self announced right handers were all positive (figure 12, red bars), ranging from 28% to 94%. We can see that removing these two elements increased the differences of laterality between both groups. The difference between the absolute values of both groups was non-significant (p > 0.05, Mann&Whitney U test).
Behavioral results

Right hand VS left hand
Concerning the scores obtained by the subjects in the Brinkman board task, we have calculated two scores for each subject: one for the left hand (blue bars, figure 13) and one for the left hand (red bars, figure 13). There was a great variability between subjects and also between hands, leading to scores ranging from 23 to 44 in 30 seconds (figure 13). In a general manner, the left-handed subjects exhibited significantly higher scores with their left hand (p<0.05, Mann&Whitney U test) (blue bar, figure 14). The right handers group, in contrary, exhibited significantly higher scores with their right hand (p<0.05, Mann&Whitney U test) (red bar, figure 15).

Figure 13: Right hand VS left hand (overview). Scores in all subjects represented with box and whiskers plots. The number of scores used for each hand is ten (n=10). The whiskers show the maximum and minimum.
Laterality VS score difference's average

This part puts in relation the scores obtained in the handedness questionnaire and in the Brinkman board task. For each subject, the differences of scores between the right and the left hand was calculated for each pairs of hands and the average of those differences were made for each subject and put in relation with the laterality scores (figure 16). The left-handed subjects had, in general, both negative laterality scores and negative differences of scores between left and right hand (blue point, figure 16). On the contrary, the right-handed subjects had generally positive values for both scores (red point, figure 16). An analysis did not show any relation between these two scores (p> 0.05, linear regression and spearman's correlation).
Male's score VS female's score

We further investigated whether the gender of the subjects influenced the performance of the task. In the group of the left-handed subjects, the women were significantly better with the right hand than men with the same hand ($p < 0.05$, according to Mann&Whitney U test), (red bars, figure 17). In the other comparisons, the statistics did not shown any significant difference ($p > 0.05$, according to Mann&Whitney U test), (blue bars, figure 17; blue and red bars, figure 18). As each group contains only the scores of five subjects, the superiority of the left handed women should be considered with care.
Horizontal VS vertical

Several studies using experimentation on monkeys showed a clear difference between the horizontal and vertical score (Rouiller et al. 1998, Freund et al. 2009). Effectively the monkeys showed a preference for vertical slots. This can be explained by the fact that making the precision grip horizontally needs more complex pattern of muscle activations than grasping the pellet from vertical slots. Does the same preferences exist in humans? The results below will bring some indications.

Figure 17: this table shows us the relation between the two sex concerning the score of both hands in Brinkman task for the left handers group. (n=50)

Figure 18: this table shows us the relation between the two sex concerning the score of both hands in Brinkman task for the right handers group. (n=50)
Figure 19: Comparison between the scores vertical and horizontal of each hand for the left handers group. (n=50)

Figure 20: Comparison between the scores vertical and horizontal of each hand for right handers group. (n=50)
In the group of subjects with left-handedness, both males and females obtained significantly higher scores in vertical slots than in horizontal slots using the left hand \((p< 0.05, \text{Mann-Whitney U test})\), (blue bars, figure 19), and significantly higher scores in horizontal slots with the right hand \((p< 0.05, \text{Mann-Whitney U test})\) (blue bars, figure 19). The right-handed subjects showed significantly higher scores in vertical slots using the left hand \((p< 0.05, \text{Mann-Whitney U test})\), (blue bars, figure 20). However, this group did not show a significant difference with their right hand (red bars, figure 20) \((p> 0.05, \text{Mann-Whitney U test})\).

In general, left-handed subjects were significantly better in vertical slots with their left hand and significantly better in horizontal slots with their right hand \((p< 0.05, \text{Mann-Whitney U test})\)(figure 21). The right-handers group showed a significant preference for the vertical slots using their left hand \((p< 0.05, \text{Mann-Whitney U test})\) (figure 20). Comparing the left hand with the right hand for the horizontal and vertical scores showed significant differences \((p< 0.05, \text{Mann-Whitney U test})\)(figure 22).
In this study, the subjects were confronted for the first time to the task of the Brinkman board. In this condition we can expect that the results would follow a learning curve. This hypothesis was confirmed by the results below. At one exception, all subjects learned while they performed the task with the repetitions. The learning slopes were ranging from -0.21 to 1.11 (e.g. figure 23, 24, annex 2). However, even if the learning slopes were always positive, there was no significant difference between hand for all groups (p > 0.05, Mann&Whitney U test), (red and blue bars, figures 25 and 26). It is important to notice that no subject had completely finished to learn after the ten repetitions (e.g. figure 23 et 24) but this remain difficult to evaluate.

Learning curves
Figure 23: evolution of the scores of left and right hand for a female with left handedness. The equations of both linear regenerations are shown above.

Figure 24: evolution of the scores of left and right hand for a male with right handedness. The equations of both linear regenerations are shown above.

Figure 25: general view of the learning slope for the left handers group. (n=5)

Figure 26: general view of the learning slope for the right handers group. (n=5)
Is there any relation between the first scores and the learning slopes? For each subjects, the data of the starting scores and learning slopes, for left and right hand, have been put together on XY graphs (figure 27) allowing us to see if there were relations. The group of left-handed subjects showed a correlation between these two scores (p< 0.05, spearman's correlation) (blue points, figure 27). On the contrary, the scores of the right handers were completely not correlated (p> 0.05, spearman's correlation), (red points, figure 27).

**Particular behavioral observations**

In some special cases, the person did not applied the grip using the thumb and the index finger but using the opposition of the thumb and the major finger. Morphological explanation? However, they applied this special grip only for time to time and it didn't lead to visible change in the results.
Discussion

The results given by the handedness questionnaire are the first important point to discuss. Those results are firstly in adequacy with the self estimation given by the subjects in this study. The right handers were really with a strong right laterality and the left handers were left lateralized (figure 10). Those data go in the same direction as several others experiments (Gallo, Angioletti & Viviani 2000, Civardi et al. 1999).

The laterality score without cultural pressure allowed us to have a more “natural” laterality estimation by suppressing the elements with strong cultural or social pressure, such as for instance item 8 where it is asked: “with which hand did you hold a knife when eating?” (see annex 1). We must keep in mind that the handedness is clearly influenced by our social rules, our world is built around the right handers people whose are about 90% of the population. For instance, instruments manufactured for right handers. This 90% has certainly an impact on the other 10%.

Concerning the scores on the modified Brinkman board task, we can see, as it could be expected, that there are significant differences between the left and the right hand in both groups. This difference is always to the advantaged laterality side (left hand for the left handers and right hand for the right handers)(figure 13, 14). In despite of those general affirmations, it is important to notice that in some cases a subject with a right handedness had a higher score with his left hand. The same is true for some left handers. Those particular results could be explained by the theory of Derakhshan (2005,2008) which says that that there is a discordance in 15% to 20% of the persons between the behavioral handedness and the neuronal handedness. Do we have, in our case, some persons with behavioral handedness (given by the questionnaire) but an opposite neuronal handedness (given by they performance in the task)? It is a probable possibility but our data did not allow us to give more evidence. Notice that the morphology of the subject can also influence the score (e.g.
large or thin finger).

The next point to discussed is why we did not observed a high correlation between the differences of scores and the laterality score. We can see (figure 6) that in general there is a strong relationship between the laterality score and differences between the scores obtained with the right and the left hand. The data of the right handers are in general positive for both score (except for two subjects that are negative for the score's difference) and the left handers group was negative for all scores (except for two subjects). The four persons with unexpected result could belong to the population described by Derakhshan.

In several cases, in this study, we are at the limit of the statistical power. In fact when we have a sample of data equal to five we are really borderline.

Concerning the preference between horizontal and vertical slots, we can see a significant difference for both hands in the left handers group and for the right hand for the right handers. Those results are quite difficult to evaluate because of the great differences between subjects in the manner to perform the task. As said before the monkey showed a clear preference for the vertical slots (Rouiller et al. 1998). This preference is not so clear in human (see tables 18, 19 and 20). The humans, contrarily to the monkeys, use different strategies to do the task: some wanted to test if one particular strategy is better than another,... We must also keep in mind that the human is formated by cultural and social environments. For example the sense of reading or writing (from the left to the right) can influence the strategies.

Finally we will discuss the learning curves data. The first thing to put ahead is that the slope for the learning curves gives an important indication about how the subject perform the task. A positive learning slope indicate a good accuracy of the subject. At one exception it was always the case in this study. The fact that we cannot reach a stable score maximum during the ten repetitions indicates that there was still a possibility for performance amelioration after ten repetitions of the task. How this element affect the results is unclear.
Conclusions

This study allows us to say that there is effectively a general correlation between the hand preference, corresponding in this test to the laterality score of the questionnaire, and the hand dominance corresponding to the score obtained while performing the task. However, some results remain unclear and the small size of the samples could explain it.

Further directions

This study, as small as it is, could be the starting point of others. Effectively, we can imagine that a similar study can be employed as control and represent a basis to evaluate a treatment against some neuro-degenerative diseases as parkinson, huntington or in cases of spinal cord injury or stroke. It can also help to a better comprehension of our nervous and motor system and allow some comparative study with the existing data on the monkeys.

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Annex 1: handedness questionnaire

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**Handedness Questionnaire**

We would like you to answer a few questions about your handedness by ringing the best answer, or by ticking in the box. If you are not certain then please leave an item blank, rather than guess.

<table>
<thead>
<tr>
<th>Question</th>
<th>Always right</th>
<th>Usually right</th>
<th>Either</th>
<th>Usually left</th>
<th>Always left</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. To hold a pen while writing a letter?</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2. To throw a ball at a target?</td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>3. To hold a pencil while drawing a picture?</td>
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<td></td>
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<tr>
<td>4. To hold a dish while drying it?</td>
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<tr>
<td>5. To turn the winder on a clock?</td>
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<td></td>
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<tr>
<td>6. To hold a jar while unscrewing its lid?</td>
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<td></td>
<td></td>
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<tr>
<td>7. To hold a thread while guiding it through the eye of a needle?</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>8. To hold a knife when eating with a knife and fork?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>9. To hold a potato while peeling it?</td>
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<tr>
<td>10. At the top of a broom when sweeping the floor?</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>11. To pick up a glass of water?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Which foot would you use to kick a ball at a goal?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. With which eye would you look through a keyhole?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

14. Which of the following diagrams most closely corresponds to the position of your hand when writing?

![Diagrams](image)

15. Has injury, damage or disease ever meant you were unable to use your normally dominant hand? No / Yes
   If Yes: How old were you? __________ years
   Which hand/arm was injured or damaged? Right / Left
   Was the effect temporary or permanent? Temporary / Permanent
   If Temporary, how long? ________
   Please describe the problem briefly: ____________________________

16. Has any person ever tried to change your handedness? No / Yes
   If Yes: Was it? From using the right hand to using the left hand / From using the left hand to using the right hand.
   How old were you when the attempt was made? __________ years
   Who was the person who tried to change your handedness? ______________
   How successful was the attempt? Very successful / Moderately / Not very / Not at all successful

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Annex 1: handedness questionnaire
Annex 2: scores for all subjects (modify Brinkman task)
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