Dissertation

# Handedness: Shortcomings of Previous Research, an Alternative Model and a New Experimental Approach

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**Abstract**

An overview of previous handedness research and a critical assessment of methods, results, and theories of this research are presented. The results of this assessment challenge the current experimental and theoretical approaches. Subsequently a new model of handedness is presented. This model is made up of four elements: (a) Handedness is associated with innate and genetically coded brain asymmetry. (b) The functional representation of handedness of left- and right-handers is mirror reversed. (c) The actual specification of handedness is determined in a random process. (d) The distribution is U-shaped with approximately 50% left-handers and 50% right-handers. The innate disposition of a majority of left-handers is changed by environmental influence, by practicing right hand writing, and by right hand tool use. Switching handedness causes differences between switched and nonswitched left- and right-handers or between left and right hand writers regarding psychological characteristics and related neuronal and physiological features. It is argued that the existence of such differences indirectly supports the new model. The alternative handedness model explains and integrates results of previous research, which do not correspond to current models and theories. Finally, ideas and considerations for an alternative approach of testing handedness are presented.

Key Phrases:
innate and genetically coded brain asymmetry
determination of handedness in a random process
50% left- and right-handers
switching handedness and consequences
psychological differences between left and right hand writers

# Contents

# Summary

The aim of this thesis is to give an overview on the research of handedness and to present a critical assessment of methods, results, and theories of this research. The results of this assessment challenge the current experimental and theoretical approaches. A new model of handedness and a new experimental approach will be proposed.

Previous methods of testing handedness (questionnaires and tests) and their results, and some theories on human (right-) handedness and on its origin will be presented. The discussion will also focus on what questionnaires and performance tests really measure (and what they do not) and whether the items and tasks can be regarded as appropriate to achieve the aimed objective. It will be argued that the current methods of measuring handedness are questionable because the questionnaire items and test tasks are selected in a particular way and the results may therefore be biased. Right-handedness, as determined by means of the traditional questionnaire or test approach, seems to be a sociocultural phenomenon. This means that the preponderance of right-handedness is a consequence of learning and instruction by the social environment and does not reflect innate handedness. Research demonstrates moreover that predominant right-handedness is limited to tool use operations.

Based on this critical review a new alternative model of handedness is suggested. This model is made up of four elements: (a) Handedness is associated with innate and genetically coded brain asymmetry. (b) The functional representation of handedness of left- and right-handers is mirror reversed. (c) The actual specification of handedness is determined in a random process. (d) The distribution is U-shaped with approximately 50% left-handers and 50% right-handers. Further features of innate handedness are the degree of handedness and the connection between handedness and lateralization of speech.

Influencing and switching handedness and its consequences will also be discussed. The aptitude of humans and animals of being instructed and influenced in their handedness differs on an individual and on a species level. The innate disposition of a majority of left-handers is changed by environmental influence, by practicing right hand writing, and by right hand tool use.

Switching handedness causes differences between switched and nonswitched left- and right-handers or between left and right hand writers regarding psychological characteristics and related neuronal and physiological features. The reported effects of shifting on motor skills, intellectual performance, spatial ability, speech impairment, personality traits, scanning direction in visual perception, drawing direction, hemispheric asymme-

try of neuronal activity, and physiological measures indirectly support the new model of handedness.

Finally, ideas and considerations for an alternative approach of testing handedness will be presented. The framework of testing (items and participants) will be discussed and six classes of test items (e.g., motor asymmetry items and coordinative tasks) will be proposed. The new approach shall indicate how it can be ensured by means of different methods of testing, item selection, and test design that testing is valid and reliable.

This alternative handedness model explains and integrates many results of previous research, which contradict one another and do not correspond to current models and theories. Further research is absolutely necessary and a new approach of testing handedness is particularly required.

## Zusammenfassung

Ziel dieser Arbeit ist es einen Überblick über die bisherige Händigkeitsforschung zu geben und eine kritische Bewertung der Methoden, Ergebnisse und Theorien dieser Forschung zu präsentieren. Die Ergebnisse dieser Bewertung stellen die derzeitigen experimentellen und theoretischen Ansätze in Frage. Ein neues Händigkeitsmodell und ein neuer experimenteller Ansatz werden vorgeschlagen.

Die bisherigen Methoden der Händigkeitstestung (Fragebögen und Tests) und ihre Resultate und einige Theorien zur menschlichen (Rechts-) Händigkeit und zu ihrem Ursprung werden vorgestellt. Es wird diskutiert, was Fragebögen und Performancetests wirklich messen (und was nicht), und ob die Items und Aufgaben zur Erreichung des angestrebten Ziel geeignet erscheinen. Es wird argumentiert, dass die derzeitigen Methoden Händigkeit zu messen, fragwürdig sind, weil die Fragebogen-Items und Testaufgaben in einer bestimmten Weise selektiert sind und die Ergebnisse deshalb verzerrt sein können. Rechtshändigkeit scheint, so wie sie mit dem traditionellen Ansatz mittels Fragebögen und Tests festgestellt wird, ein soziokulturelles Phänomen zu sein. Dies bedeutet, dass das Überwiegen von Rechtshändigkeit eine Folge von Lernen und Instruktion durch das soziale Umfeld ist und daher nicht die angeborene Händigkeit widerspiegelt. Die Forschung zeigt ferner, dass überwiegende Rechtshändigkeit auf die Verwendung von Werkzeugen und Gegenständen begrenzt ist.

Auf diese kritische Bewertung aufbauend wird ein neues alternatives Händigkeitsmodell vorgeschlagen. Dieses Modell besteht aus vier Elementen: (a) Händigkeit ist mit einer angeborenen und genetisch kodierten Hirnasymmetrie verbunden. (b) Die funktionale Repräsentation der Händigkeit ist bei Links- und Rechtshändern spiegelverkehrt. (c) Die tatsächliche Ausprägung von Händigkeit wird in einem Zufallsprozess festgelegt. (d) Die Verteilung ist U-förmig mit ungefähr 50% Linkshändern und 50% Rechtshändern. Weitere Charakteristika der angeborenen Händigkeit sind die Stärke der Händigkeit und der Zusammenhang zwischen Händigkeit und der Lateralisation der Sprache.

Das Beeinflussen und Umschulen von Händigkeit und die Konsequenzen dessen werden diskutiert. Die Fähigkeit von Menschen und von Tieren in ihrer Händigkeit instruiert und beeinflusst zu werden unterscheidet sich auf der Ebene der Individuen und der Arten. Die angeborene Veranlagung einer Mehrheit von Linkshänder wird durch Umwelteinflüsse, durch das rechthändige Schreiben und durch das rechtshändige Verwenden von Werkzeugen und Gegenständen verändert.

Die Umschulung der Händigkeit löst Unterschiede zwischen umgeschulten und nicht

umgeschulten Linkshändern bzw. zwischen linkshändig und rechtshändig Schreibenden hinsichtlich psychischer Eigenschaften und bei den damit verbundenen neuronalen und physiologischen Merkmalen aus. Die berichteten Auswirkungen der Umschulung auf motorische Fertigkeiten, intellektuelle Leistung, räumliche Begabung, sprachliche Beeinträchtigungen, Persönlichkeitseigenschaften, die Abtastrichtung bei visueller Wahrnehmung, die Richtung beim Zeichnen, die hemisphärische Asymmetrie der neuronalen Aktivität und physiologische Messwerte untermauern das neue Händigkeitsmodell indirekt.

Anschließend werden Ideen und Überlegungen für einen alternativen Ansatz der Händigkeitstestung vorgestellt. Die Rahmenbedingungen des Testens (Items und Teilnehmer) werden diskutiert und sechs Klassen von Testitems (z. B. Items zur Feststellung motorischer Asymmetrien und koordinative Aufgaben) werden vorgeschlagen. Der neue Ansatz soll Hinweise darauf geben wie durch unterschiedliche Testmethoden, durch Itemauswahl und durch das Testdesign sichergestellt werden kann, dass eine Testung valide und reliabel ist.

Dieses alternative Händigkeitsmodell erklärt und integriert viele Ergebnisse der bisherigen Forschung, die sich gegenseitig widersprechen und nicht mit den derzeitigen Modellen und Theorien übereinstimmen. Weitere Forschungstätigkeiten sind daher unerlässlich. Insbesondere ist eine neue Vorgehensweise bei der Händigkeitstestung erforderlich.

# 1 Introduction

Human handedness has been discussed for more than a hundred years but until now it has not been clear how it should be perceived and how it can be adequately measured. Right-handedness occurs in about 90% of all humans, and approximately 10% of the population seems to be left-handed (Hardyck & Petrinovich, 1977). It is furthermore unclear and under discussion, whether human hand preference, especially the strong tendency to right-handedness, is innate and genetically determined (Annett, 1985; Corballis, 1997; McManus, 1985b) or whether it is learned and influenced by the environment and depends on enforcement, example, and experience (Provins, 1997).

In mammal species a distinct hand or paw preference can often be found at least in 80% of all individuals. However, a bias towards a preponderance of left-handers or right-handers on population level cannot be ascertained for mice (Collins, 1968, 1969, 1970), rats (Peterson, 1934), and chimpanzees (Finch, 1941). Further testing showed that the paw preference of an individual mouse is innate (Collins, 1975) but not genetically determined (Collins, 1969). Moreover, animal hand preference can be influenced. By observing a mouse, which acted as a teacher, male mice learned to open a pendulum door in the same direction as the teacher did it (Collins, 1988). The preferential hand use of monkeys for picking up food was modified by training and in 5 out of 6 monkeys the new habit has retained for months after the end of the training (Kempf, 1917).

For humans and animal species corresponding results exist. Most individuals are lateralized in any direction, left or right. The distinct discrepancy between a preference for the right hand in humans (ratio of 90:10 towards right-handedness) and the absence of hand preference in animal species (ratio of 50:50) is widely accepted. Human right-handedness on population level is explained by several approaches of reasoning (an overview can be found in Beaton, 2003; Harris, 1992; Van Strien, 2000). The core of all attempts to explain the discrepancy seems to be that the development and formation of handedness in human species is seen as very different from development and formation of handedness in animal species. Thus, humans are the only species with a notable level of right-handedness. Corballis (1989) conceived right-handedness as "almost certainly universally human, in the sense that it is a characteristic of all human cultures (Corballis, 1983). This suggests that it is a biological rather than a cultural endowment" (p. 493). Provins (1997) instead states that right-handedness is caused by environment and culture. Humans are, irrespective of whether one or both of these ideas are true, by majority and for some specific reasons (genes and/or culture) seen as right-handed with a lateralization of speech in the left hemisphere. Human right-handedness is conceived as “species-unique” (Warren, 1980, p. 357).

In this thesis I want to again address the questions as to whether right-handedness in the human species and consistent manual preference in an individual is innate and genetic or whether this is caused by environment, learning, and influences. My answer on this question is twofold:

1. Innate is (a) a consistent manual preference in almost all individuals and (b) a 50:50 distribution of left and right hand preference in all mammals, including the human species, on species level. Genes are, according to Morgan (1977) and Collins (1977), left-right agnosic, they cause asymmetries (on the level of individuals) but do not code for the direction (neither on individual nor on population level). Whether an individual (human or animal) becomes left-handed or right-handed is a matter of chance (50:50), that it becomes either left-handed or right-handed (i.e., right- or left-brained) is a matter of genes.

2. In humans a 90:10 distribution on population level can currently be determined. Therefore, the manual specialization in roughly 40% of the population must have been switched from left to right hand preference by enforcement, by imitating a role model, by familiarization, by observational learning, or by other environmental influences.

Such influence is stronger in activities, which are more socially controlled like eating or writing, and is weaker in activities like carrying a bag or opening a bottle. Thus, questionnaires often show that writing is one of the activities, which are most often performed with the right hand (Annett, 1970; Beukelaar & Kroonenberg, 1983; Bryden, 1977; Dahmen & Fagard, 2005). In some societies almost everyone has a right hand preference, at least for activities like writing. For example, in a study in Taiwan (Teng, Lee, Yang, & Chang, 1976) only 0.7% of 4,143 participants were left hand writers (LHWs). From an analysis in Katanga, Congo it is reported that 0.5% of 1,047 children were left-handed but no child was writing with the left hand (Verhaegen & Ntumba, 1964). This would make nearly 50% of the population in both societies shifted in hand preference, especially in writing hand (the seriousness of a switched writing hand will be discussed later on).

Based on the above two theses that handedness is (a) innate with a 50:50 ratio and (b) switched in 40% of the population, it is the ambition of this thesis to demonstrate that human hand preference and hand use may be shifted (the terms *switched* and *shifted* are used synonymously with respect to the term handedness) to an immense extent.

The first measure in the argumentation is the presentation of an alternative theory of handedness or more general a theory of asymmetry of the brain. This theory incorporates the idea of lateralization of both motor dominance and speech. The animal model is a blueprint for this theory as we will see. According to the theory handedness is seen as innate but nongenetic, unidimensional, and dichotomous, and the preference for either the left or the right hand is distributed with a ratio of 50:50. In this thesis the term handedness will be perceived in a wider sense as it was until now. Handedness in a sense of a dominant or preferred hand is only one aspect of laterality. Handedness means that not only a hand is dominant but also a foot, a leg, and possibly an eye or an ear. Therefore, the term sidedness would be more self-explanatory.

Because of the neural plasticity of the brain the innate dominance is proposed to be switchable. The degree of switching and the permanence of switching depend on species specific and individual aptitude (e.g., manual and intellectual capability, attention, or understanding of instruction) and environmental circumstances (e.g., social enforcement to switch writing hand or other manual activities, experience, role model, or disposability of left- or right-handed tools). With respect to the effectiveness of such factors an individual may perform some or all activities always or often in a manner inconsistent with the inborn preference.

The second measure in verifying the theses is to draw conclusions and infer propositions from the suggested theory and to demonstrate that empirical and experimental evidence for the theory and the derived conclusions and propositions can be provided. It will also be shown that results from studies with very diverse methods (e.g., direct observation of manual activity or brain imaging techniques), with selected groups of human participants (e.g., offspring from left-handed parents, children, clinic patients, or illiterates), and with animals provide some affirmation of the theory.

The aim of the proposed theory is to explain some inconsistencies in several theories, which apparently demonstrate a preponderance of right-handedness: For example, genetic models cannot explain a continuing decrease in right-handedness and an increase in the frequency of left-handers during the 20th century. Environmental and genetic models of left-handedness are also contradictory.

The suggested shift of manual preference of about 40% of human population is certainly an interesting research topic on its own. Nevertheless, I want to add another topic and discuss in this thesis the impact of switching hand preference particularly the switching of the writing hand. Some direct and indirect evidence indicates that switching the writing hand may cause some severe and negative consequences like stuttering (Ballard, 1911-12), disturbed learning efficiency (Rett, Kohlmann, & Strauch, 1973), dyslexia, and dysgraphia (Sovák, 1968).

After this introduction the thesis proceeds in the second section with a short overview of previous research and its theories and results. Following this, I will discuss methods and results of testing, theories of handedness, and the inconsistencies between theories and results. The third section presents a new theory of human handedness in detail and tries to give some substantiation of the theory. This section also deals with the matter of switching the writing hand and the related consequences and problems. The fourth section presents ideas and gives recommendations concerning a new experimental approach of measuring handedness and the fifth section comprises some final remarks.

The argumentation of the entire thesis is of theoretical nature and exclusively founded on results of published studies. Apart from a few exceptions, the results from experiments, which are based on the suggested new experimental approach, are not presented. Nevertheless, the fourth section is an integral and necessary part of this work.

# 2 Previous Research: Methods, Results, Theories, and Discussion

The first subsection of this section gives a very brief overview of previous research. Although commonly known it is worthwhile summarizing a few methods, results, and theories in the first subsection, because the alternative model of handedness or more precisely a general model of sidedness, which is presented in the third section, and the new method of testing lateral preference, which is proposed in the fourth section, are entirely different from all previous approaches. A discussion of methods, results, and theories follows in the second and third subsections.

## 2.1 Previous Methods, Results, and Theories

The measurement of hand preference is mostly performed by administering questionnaires to participants (Oldfield, 1971; Annett, 1970; Crovitz & Zener, 1962; Raczkowski, Kalat, & Nebes, 1974). These questionnaires contain usually about 10 to 20 questions. In each question respondents are asked to mark which hand they prefer to achieve an action (e.g., writing or using a toothbrush). The tasks in these and other questionnaires are usually performed with one hand and mostly with an object or tool (e.g., pen, toothbrush, or scissors). Bimanual items and items conducted by a foot or leg are very rare. Chapman and Chapman (1987) verified reliability and found high internal consistency (coefficient $\alpha = 0.96$ for both sexes) and high test-retest reliability (r = 0.97 for males and r = 0.96 for females) by using 13 items selected from the questionnaire by Raczkowski et al.

Additionally, a wide range of performance tests exist. The participants of such a test usually have to perform a manual task as fast and precise as they can. Many of these tests determine the participants' performance in tasks, which resemble writing or drawing, like Bishop's (1980) square tracing task, Bishop's (1984) square marking task, Steingrüber's (1971) test, and three of five tasks (squares, dots, and lines) in Annett's (1992) test. Other tests like Annett's two other tasks (pegs and holes), the test by Perelle, Ehrman, and Manowitz (1981), and the card reaching test by Bishop, Ross, Daniels, and Bright (1996) challenge as well the participants' fine motor skills.

A particular point of interest in measuring is the dimensionality of hand preference. Questionnaires with 32 to 75 items were used by Beukelaar and Kroonenberg (1983), Bryden, MacRae, and Steenhuis (1991), Healey, Liederman, and Geschwind (1986), Peters and Murphy (1993), Provins, Milner, and Kerr (1982), Steenhuis and Bryden

(1989), and Steenhuis, Bryden, Schwartz, and Lawson (1990). Factor analysis of questionnaire data suggests a multidimensional understanding of hand preference (Bryden, 1977; Bryden et al.; Healey et al.; Steenhuis & Bryden; Steenhuis et al.). Hand preference can be explained by the first factor *skilled items* (e.g., writing, drawing, throwing, and using a toothbrush), which accounts for a high proportion of variance. Other factors represent *unskilled items* like picking up or carrying objects. Each of these factors accounts only for a few percent of the total variance. To obtain unambiguous results Bryden (1977, 1982) proposed to use only five items with high factor loadings (writing, drawing, throwing, using a toothbrush, and cutting with scissors) out of the group of the skilled items. Thus, handedness would be perceived as hand preference in skilled activities. McManus (1985a) and Perelle and Ehrman (1994) suggested using only one item, the writing hand. In their view the (usually right) writing hand is an indicator for a consistent manual preference and right-handedness is accompanied by lateralization of speech in the left hemisphere in almost all humans.

Main objectives in measuring hand preference are (a) to estimate a ratio of left- and right-handed individuals and (b) to demonstrate that humankind is by majority right-handed. Most questionnaires, like those proposed by Annett (1970), Chapman and Chapman (1987), and Oldfield (1971) were administered to undergraduate students at American or British colleges. Regardless whether handedness should be understood as dichotomous or continuous all studies present that a great majority of the sample is right-handed. In an international comparative study by Perelle and Ehrman (1994) and in an overview by Hardyck and Petrinovich (1977) it was shown that about 2% to 14% of the population is left-handed depending on the time and place of the study and the age or year of birth of the participants. The rest is right-handed or at least mixed-handed with mostly right writing hand. Ellis, Ellis, and Marshall (1988) made an effort to get a more representative sample than those in other studies and draw a sample, with participants from all ages and both sexes, representing the entire population. They determined with Oldfield's questionnaire the hand preference of a large number of participants ($N = 6{,}097$). The additional expense made by drawing a representative sample does not provide an additional gain as the distribution of handedness is not sufficiently different from the distribution of other researchers. Like in many other studies in Western (Bryden, 1977; Bryden et al., 1991; Gilbert & Wysocki, 1992; Oldfield; Smart, Jeffery, & Richards, 1980; Steenhuis & Bryden, 1989) and non-Western countries (Dahmen & Fagard, 2005; Ida & Mandal, 2003; Shimizu & Endo, 1983; Teng, Lee, Yang, & Chang,

1979) males tended more to be left-handed (8.44%) than females (7.38%) according to the study by Ellis et al. Also younger participants tended to be more left-handed (10% of females and 14% of males in their 20s) than older participants (4% of females and 8% of males in their 60s). This result was also confirmed by other studies (Ashton, 1982; Bryden; Brackenridge, 1981; Dahmen & Fagard; Fleminger, Dalton, & Standage, 1977; Gilbert & Wysocki; Hugdahl, Satz, Mitrushina, & Miller, 1993; Smart et al.; Spiegler & Yeni-Komshian, 1983; Tambs, Magnus, & Berg, 1987).

The question as to why humans are as a majority right-handed and the question about the origin of left-handedness are the most controversial discussed topics in research of handedness. Two genetic models, which seem currently to be the most influential, will be presented in this short overview. Additionally, a brief description of other models of left-handedness, which seem to have minor influence, will follow.

After many attempts (for overviews see, Hardyck & Petrinovich, 1977; Harris, 1992) two models by Annett (1985) and by McManus (1985b) are broadly accepted. These models are more consistent with the data from many studies on hand preference and familial relationships than other models. The competing but somewhat similar genetic models by Annett and McManus propose that hand preference is controlled by two genes, $rs^+$ and $rs^-$ in Annett's model and D and C in McManus' model, at a single locus.

In Annett's (1985) right shift theory the right-shift gene ($rs^+$) shifts the distribution of skill differences between both hands towards the right. The appearance of the $rs^+$ gene causes an individual to be more skilled with the right hand. The $rs^-$ gene induces neither a shift to a more skillful right hand nor to a more skillful left hand. As there are three possible subgroups of individuals with $rs^{++}$, $rs^{+-}$, and $rs^{--}$ combinations of genes, Annett proposes different probabilities of becoming right-handed (i.e., have a better skilled right hand) for each of the three groups. The proportion of left-handed individuals in the population depends (a) on the shape of the skill difference distribution function for the three groups, (b) on the probability of each gene combinations or rather on the frequency of the $rs^+$ and $rs^-$ gene in the population, and (c) on the relative strength of skill differences caused by the right shift gene in single ($rs^{+-}$) or double dose ($rs^{++}$). For example, the total lack of the $rs^+$ gene (i.e., an individual of $rs^{--}$ genotype) makes a person either a left-hander or a right-hander in phenotype. Each with a probability of 50%.

McManus' (1985b) model differs conceptually in two important constituents from the above model. First, the gene which induces handedness does not generate a relative difference of manual skills, but a preference for one or the other hand. Second, chance is only linked to the C gene. The D gene always codes for right-handedness. The homozygous combination DD codes for 100% right-handers, the combination DC codes for 75% right-handers, and CC codes for 50% right-handers. The probability of each gene combination and finally the share of left- and right-handers in the population depend on the frequency of the D and C genes in the population. As a direct way to determine the frequency of the $rs^+$ and $rs^-$ or the D and C gene in the population does not exist, such parameters can be estimated only from data on the inheritance of left and right hand preference in families. With respect to the models of Annett (1985) and McManus, Corballis (1997) suggested that they dealt with the same phenomenon in a similar way: "There seems to be no reliable way at the present time to distinguish empirically between them" (p. 716).

With the concept of pathological left-handedness (PLH) Satz (1972), Satz, Orsini, Saslow, and Henry (1985), and Soper and Satz (1984) formulated a theory of left-handedness, which should explain a special case of left-handedness. PLH is not understood as a general theory, but as a model in addition to the model of genetically influenced left-handedness in normal individuals. Hence, PLH occurs in clinical patients, which are naturally right-handers but switched to a consistent left hand preference due to lesions of the left hemisphere. The reversed incident, a shifting of a left-hander to right hand preference (i.e., pathological right-handedness), can be observed more infrequently than PLH. The incidence of left-handers is already lower as left-handedness is caused by genes ($rs^-$ or C), which are more rarely than genes evoking right-handedness.

The role of learning is seen as another factor of handedness. One branch of the theory of learning postulates that a fraction of originally right-handed infants become left-handed, because they begin using the left hand in early life, are successful, are reinforced, and therefore become more and more left-handed despite differing predisposition (Perelle et al., 1981, p. 971). Another branch of theory (Hertz 1909/1960; Provins, 1997) does not assume a predisposition of humans (and animal species) in either direction, but understands handedness and consistent manual preference as completely acquired. Different symbolic qualities are attributed to both hands and right-handedness is seen as "an ideal to which everybody must conform and which society forces us to respect by positive sanctions" (Hertz, p. 93). Therefore, the right hand is preferred and used more, and humans become by majority right-handed because of higher cultural valuation of right-handedness and more suitable training. Provins picked up this concept and described a model of environmentally and culturally induced right-handedness, which integrates modern findings about learning and neural plasticity. Provins stated:

> Handedness characteristics of each individual are primarily the product of (a) that subject's particular motor learning capacity (which is inherently the same for both the right and left sides) and (b) the extent of that individual's exposure to environmental bias, or the history of relative usage and experience of each hand. (p. 564)

An overview of the discussed theories and other models like the testosterone hypothesis (Geschwind & Galaburda, 1987) or the developmental instability model (Gangestad & Yeo, 1994; Yeo & Gangestad, 1993; Yeo, Gangestad, & Daniel, 1993) can be found in Beaton (2003), Hardyck and Petrinovich (1977), Harris (1992), or Van Strien (2000).

All the above discussed aspects of human handedness have been reviewed by Beaton (2003) as follows:

> (a) The majority of the population has a stronger, faster and more accurate right hand; (b) handedness has a familial component; (c) males tend to be more frequently left-handed than females; (d) handedness is a continuum; (e) relative differences in skill between preferred and nonpreferred hand depend upon variation in level of skill of the nonpreferred hand. (p. 111)

Beaton (2003) concludes, "These are the minimal observations that any complete theory of handedness needs to address" (p. 111).

## 2.2 Discussion of Methods and Results of Testing

The above mentioned results of handedness research seem very obvious, especially the result that the majority of the population is right-handed (cf. Beaton, 2003). Nearly every study demonstrated (even for more or less representative samples) that a proportion of about 10% of the population is left-handed.

In this section it will be discussed what questionnaires and performance tests really measure (and what they do not) and whether the items and tasks seem to be appropriate for the aimed objective. The methods of testing are questionable because the questionnaire items and test tasks are selected in a particular way and the results may therefore be biased. First, a general discussion of research, which comprises of four objections against the way of testing (parts 2.2.1 - 2.2.4) and considerations concerning what is actually measured (part 2.2.5), follows in this subsection. Something that will also be addressed is what should be tested and how testing should be conducted when measuring handedness (part 2.2.6). Second, the methodology of testing handedness (part 2.2.7) is reconsidered from a conceptual and from an experimental point of view.

### 2.2.1 Questionnaire Activities are Socially Influenced

Many manual activities, which are often used as items in questionnaires, are instructed: When learning to execute an activity, children may either be instructed which hand the activity should be performed with, or they imitate the instructor's hand preference on their own.

The item *writing hand* is suggested to be a very good indicator of handedness (McManus, 1985a; Perelle & Ehrman, 1994) and is used for determination of handedness (Ashton, 1982; Brackenridge, 1981; Gilbert & Wysocki, 1992; Perelle & Ehrman; Smart et al., 1980; Spiegler & Yeni-Komshian, 1983). Even when writing is not used as the only criterion for determining handedness most questionnaires ask for the writing and drawing hand.

These two items cause particular doubt that the writing and drawing hand is a good and unambiguous measure for handedness because the writing hand is switched. In Western and non-Western cultures a social norm of right hand writing exists, which is enforced more or less completely throughout society.[1]

Switching left-handers in the writing hand was very usual in Western societies at least until the fifties of the last century. Beukelaar and Kroonenberg (1986) found in a sample of 73 Dutch self-professed left-handers born between 1910 and 1939 that not a single person was writing with the left hand, whereas out of 94 left-handers born after 1960, all but 1 were writing with the left hand. In four other European countries (Spain, Greece, Italy, and France) the probability of a left writing hand is also higher for left-handers born after 1960 (Dellatolas et al., 1991). For a US sample Hugdahl et al. (1993) reported that 100% of left-handers in their 90s have a shifted writing hand. The switching rates decline to 10% or 20% for younger left-handers. A comparable result provides Tan (1983, p. 867). By using a questionnaire he identified about 50% more left-handers among older individuals than by asking only for the writing hand. In 2004 to 2006 I found in an Austrian sample (mostly students) that 15 of 98 left-handers were switched in writing

[1] In languages with scripts from left to right like English or German right hand writing affords minor advantages compared to left hand writing. But these advantages seem to be small compared to the disadvantages of switching the writing hand of left-handers (cf. Ballard, 1911-12; Rett et al., 1973; Sovák, 1968).

hand. Ten of these students were in their 20s, 3 in their 30s, and 2 were older than 50 years. Apparently switching handedness was accomplished in Austria in the 1980s. The suppression of left hand writing may have decreased in Western countries, but in other non-Western cultures it still seems to be very common at least until the 1990s. Ida and Mandal (2003) and Shimizu and Endo (1983) found in samples of Japanese students that more than 70% of all left-handers were switched in writing hand. Teng et al. (1976, 1979) reported for a Chinese student population in Taiwan that more than 75% of the left-handers were shifted. In a Chinese student sample in Hong Kong one of three left-handers were switched (Hoosain, 1990). Also in the Ivory Coast and Sudan, pressure exists towards right hand writing (de Agostini, Khamis, Ahui, & Dellatolas, 1997). This pressure is more often reported by respondents with overall left hand preference for 20 items (47% in Ivory Coast, 36% in Sudan) than in individuals with right preference (11% in Ivory Coast, 3% in Sudan).

Searleman and Porac (2001) reported in a study on right shift attempts concerning the writing hand that more than 80% of left-handers at the age of 65 to 100 years experienced shift attempts, which were successful in 70% of all left-handers. A study with a younger group (18 to 40 years of age) and an older group (40 to 94 years of age) of participants confirmed the results (Searleman & Porac, 2003). In the group of 40 to 94 years of age 66% of all left-handers reported right shift attempts (successful in 33% of all left-handers). In the group of 18 to 40 years of age only 30% of left-handers experienced shift attempts, which were successful only in 7%. Also in a sample of 650 students with a mean age of 19 years (probably born in the early 1960s) 11.2% of all students experienced attempts to change hand preference for writing and other activities (Porac, Coren, & Searleman, 1986). Most often were the shift attempts towards the use of the right hand (8% of the total sample). In the right shift group the change of hand preference was successful in 47% of 45 respondents. The higher rates of successful switching in females (62%) compared to males (26%) could be one reason for a lower incidence of left-handedness in females. The respondents reported that they experienced by majority pressure to change hand preference before 8 years of age. The authors noticed that "overt pressure on hand preference patterns is a contemporary phenomenon that has continued through the 1960s" (Porac et al., p. 259). This is remarkable as Canada and the US are the most liberal societies regarding left-handedness. The study by Perelle and Ehrman (1994) showed for Canada the highest frequency of LHWs (12.8%), followed by the US (12.2%) and then other Western countries (England, Netherlands, and Australia).

Corresponding with a decreasing pressure against left hand writing over the years (from generation to generation) a growing share of LHWs is noticeable (Ashton, 1982; Brackenridge, 1981; Fleminger et al., 1977; Gilbert & Wysocki, 1992; Hugdahl et al., 1993; Smart et al., 1980; Spiegler & Yeni-Komshian, 1983; Tambs et al., 1987). Nevertheless, writing is one of the activities, which is most frequently performed with the right hand (Annett, 1970; Beukelaar & Kroonenberg, 1983; Bryden, 1977; Dahmen & Fagard, 2005; Tan, 1983 [only older persons]). A relevant fraction of the individuals who are classified as left-handed are writing with the right hand (Ashton; Beukelaar & Kroonenberg, 1986). This is for example true for more than 55% of left-handed persons in the sample of Beukelaar and Kroonenberg (1986).

Taking all these results into account the writing hand is an unsuitable criterion to determine handedness because of a social norm and shift attempts. Data regarding the writing hand are biased and the extent of switching is inevitably unknown.

Also other activities, which are used as items in questionnaires, can be influenced by a traditional social norm or are instructed in a way that influences hand preference: For eating, regardless whether with hand, spoon, cutlery, or chopsticks, in many cultures a norm exists and children are more or less instructed in a certain way. Items like throwing, use of rackets, baseball bats, or toothbrushes could be too difficult for infants, and their motor capacity may be too low to find motions on their own when they are learning to perform these activities. Therefore, it is possible that the sidedness of motions is imitated from adult instructors. This objection holds for scissors as well. Moreover, this tool is normally designed for right hand use. The use of scissors as a questionnaire item conflicts with a criterion of item selection: Beukelaar and Kroonenberg (1983) claim that "tasks should not favour either hand outright" (p. 34) but violate this demand by using the questionnaire item *scissors* in their own questionnaire.

The activities discussed above are cultural skills and are adopted in a longer process. Usually children at the age of 2 to 6 years are instructed how to use tools and objects, which are common in our environment. It is unknown (a) whether children choose by themselves which hand they prefer to use, (b) whether they are instructed regarding the hand the activity should be performed with, or (c) whether children imitate by themselves the hand preference of the instructor. Adults perform these activities with a low level of attention. This may lead to the assumption that this is also true for children. However, children are learning and conducting these techniques, especially writing, with a high level of concentration. Finally, activities, which are influenced by a social norm, which may cause a switching of hand preference, are not appropriate to measure handedness. This is true when handedness is understood as an innate feature, like genetic theories propose and as I understand it to be as well.

### 2.2.2 Questionnaire Items are not Dissimilar Enough

Items from questionnaires focus too much on a limited scope of handedness. The items are mostly performed unimanual (rarely bimanual) with an object or tool and the results are biased and of limited value.

Factor analysis of questionnaire data (Bryden, 1977; Bryden et al., 1991; Healey et al., 1986; Richardson, 1978; Steenhuis & Bryden, 1989; Steenhuis et al., 1990) demonstrated that skilled items have high loadings in the first factor, which accounts for a high proportion of total variance. The similarity of these items, which require fine motor skills, is seen as a strength of the present concept of measuring handedness and a test with five items (writing, drawing, using a toothbrush, throwing, and cutting with scissors) "seems to be the best preference measure of handedness that we now have available" (Bryden, 1982, p. 164; see also Bryden, 1977).

Quite the opposite is correct: The findings of the factor analysis (skilled items in the first factor with high factor loadings) are overvalued and a questionnaire with item selection based on the results and ideas of factor analysis is for the following reasons of limited benefit:

First, the results of the factor analysis are less general than it is claimed. Peters and Murphy (1993) pointed out that a factor analysis of pooled questionnaire data is questionable, because the between group differences may be the reason for the clear result of the analysis. Two separated factor analyses for left- and right-handers achieved results (factors, loading items, and factor loadings) that were strongly differing from each other and were different from the results of an analysis with pooled data.

Second, the limitation on few items, which require fine motor skills, may be a problem for the validity of the results, as items, which may show less clear but more important and more valid results, might be ignored. For example, Steenhuis and Bryden (1989, p. 296) found that 23.5% of males were classified as left-handed and another 4.2% as ambidextrous when classification of handedness was carried out by means of the third factor in the factor analysis on which two items loaded ("Do you consider yourself a left-handed or right-handed baseball batter?" and "Over which shoulder would you swing an axe?"). A classification on account of the first skilled items factor led to 10% male left-handers. For the same two items Bryden et al. (1991, p. 484) reported a comparable result with shares of non-right-handedness in both sexes and different age groups between 14% and 28%. On the one hand, it is usual that items like these are dismissed so far as they explain only small parts of the variance. On the other hand, the effort to examine the strengths and weaknesses of such items in handedness classification has not been made, but may be worth a lot.

Third, the switching of the writing hand is associated with an overall right shift of other activities. Searleman and Porac (2001) recorded preference data for writing and four other activities (eating with a fork, throwing a ball, holding a match while striking it, and picking up a glass of water) from participants of 65 to 100 years of age. Left-handers who had never switched to the right writing hand and left-handers who reported an unsuccessful right shift attempt had a noticeable different manual preference score than switched left-handers (SLHs, the term switched means switched writing hand) had. SLHs did not only resemble right-handers in writing hand preference but in general hand preference. Tan (1983) administered the Crovitz and Zener (1962) questionnaire to the parental and filial generation of families and reported that the parental generation did not only perform writing but also other manual activities less often with the left hand than the filial generation. Left-handers in the older generation were obviously not only switched in writing hand but also in other activities and finally many of them were not identifiable as left-handers, but performed like right-handers and were considered as such. As this work will subsequently show, this conclusion is based on the plausible assumption that, for whatever causes, left-handedness is innate and the prevalence in the younger generation is not above the normal frequency of left-handedness. In this case the lower incidence of left-handers in the older generation must be caused by some social or cultural factors and not by disparities of the gene pool. The gene pool (i.e., frequency of genes causing right- or left-handedness) cannot be subject to variations that may cause a strong increase of left-handedness within a generation. When the result proves true that a writing hand shift comes along with a general shift of hand preference in items used by Searleman and Porac or Tan in their studies, then it is pointless to test with items from the group of skilled items. The hand preference in items of this group and the preference for writing hand are too similar. In other words, the answers on up to 75 items of a common questionnaire are worth as much as the answer to the question: "Which hand are you writing with?" (The value of this answer has been discussed already. It might be very low.)

Fourth, bimanual tasks and tasks without tools and objects are almost not included in questionnaires. Compared to all motor activities achieved by an individual, questionnaires cover only a very small fraction of human motor behavior. Marchant, McGrew, and Eibl-Eibesfeldt (1995) reported that in film material from traditional cultures 8,629 hand activities were identifiable. Only 14% of 6,150 unimanual acts were tool use acts. The majority of 86% nontool acts were not a matter of interest in handedness research with questionnaires until recently.

### 2.2.3 Results from Performance Tests and Questionnaires are Similar

Various methods of testing hand performance with manual tasks provide similar results than questionnaires because tests are focused on fine motor activities and the writing hand is mostly the better performing hand. In many tasks LHWs perform better with the left hand, and right hand writers (RHWs) are more skillful with the right hand.

Participants of performance tests are usually asked to perform a manual task as fast and precisely as they can. The tests consist of three types of tasks: (a) Tasks like writing or drawing with timekeeping like Bishop's (1980) square tracing task, Bishop's (1984) square marking task, Steingrüber's (1971) test (tracing, tapping, and dotting), or three of five tasks (squares, dots, and lines) in Annett's (1992) test; (b) tasks of fine motor activities like Annett's two other tasks (pegs and holes) where small parts have to be moved from one place to another, the test by Perelle et al. (1981), or the card reaching test by Bishop et al. (1996); and (c) a tapping task with a finger, the thumb, or the whole hand (e.g., Bishop et al.).

Thus, questionnaires and performance tests determine similar capabilities: Performance or preference in fine motor activities, which demand coordinative proficiency. Certainly, questionnaires inquire manual preference and tests determine motor skills, but three studies show that performance and preference are not independent. (a) Annett (1992) found that left-handers (determined either by writing hand or by a hand preference test [Annett, 1970] with 12 items) perform better with their left hand. For right-handers the contrary can be confirmed. For three items (dots, lines, and holes) Annett (1992) reported that approximately one or two percent of all participants (roughly 10% LHWs and 90% RHWs) performed better with the nonwriting hand (p. 594). (b) The result of an experiment where participants had to move small parts with tweezers (Perelle et al., 1981) is that LHWs performed better with the left hand than with the right hand and RHWs performed better with the right hand than with the left hand regardless whether learning sessions were given or not. (c) The participants' performance with either hand was measured by Tapley and Bryden (1985) in a dotting test. LHWs as well as RHWs demonstrated overall a better performance with their writing hand than with the nonwriting hand. Only 8 of 1556 participants (0.5%) performed better with the nonwriting hand.

Tasks in performance tests are essentially similar to items in questionnaires and the results of tests and questionnaires refer to the same feature of fine motor skills, which are trained and instructed. It is not surprising that fundamental results of handedness research, as summarized by Beaton (2003), can be replicated by using performance tests instead of questionnaires. Again it is true that all the testing seems to be worth as much as the answer to the question "Which hand are you writing with?".

#### 2.2.4 The Current Concept of Handedness is Restricted

Questionnaires focus too much on handedness and fail to explore a preference for a foot, an eye, or an ear, or more generally, to study how an individual behaves in space and moves and stabilizes his or her body. Presuming a broader concept of handedness, which includes not only a hand as being dominant or preferred, but also a foot, a leg, and eventually an eye or an ear, a different method of testing is necessary and new items have to be found.

Research on footedness showed that left-footedness is more frequent than left-handedness (Dahmen & Fagard, 2005; Kang & Harris, 2000; Peters & Durding, 1979; Teng et al., 1979). Kang and Harris examined for Korean participants the congruence of handedness and footedness especially in left-handers. Sixty-three percent of 35 left-handers, mostly RHWs, were left-footed. In a comparison of two groups of left-handers, one made up of consistent left-handers who performed at least six of eight tasks with the left hand, and another one made up of inconsistent left-handers who performed less than six tasks with the left hand, they found out that all left-footers were consistent left-handers. The left-handed but right-footed were by majority (54%) inconsistent left-handers. A possible interpretation of this result may be that (a) left-handedness is accompanied by left-footedness and (b) switching or suppressing left-handedness influences as well the degree of left-footedness.

For three groups of left-handers with differing extent of switched handedness (switched, unsuccessful switching attempts, and no shift attempts) Searleman and Porac (2001) reported that the degree of left-footedness decreases with the extent and success of shift attempts. This indicates as well that switching footedness comes along with switching handedness. However, even when laterality of handedness and footedness are natively conjoint (both left-sided or both right-sided), it can be expected and easily be explained by a greater impact of instruction and a social norm concerning handedness (and not concerning footedness) that left-handedness is more frequently switched than left-footedness. Therefore, left-footedness is more common than left-handedness.

For eyedness the results are ambiguous: Left-eyedness is more frequent than left-footedness or left-handedness (Dahmen & Fagard, 2005; Dawson, 1972, 1977; Hoosain, 1990; Teng et al., 1979), and left-handedness and left-eyedness are related (respectively right-handedness and right-eyedness). However, the correlation between handedness and eyedness seems to be weaker than the correlation between handedness and footedness (Hoosain; Teng et al.).

### 2.2.5 What Questionnaires Really Measure

The four above objections (parts 2.2.1 - 2.2.4) raise the presumption that questionnaires and performance tests do not determine handedness (or rather sidedness) but measure something like the enforcement and impact of a social norm. They are biased because of instruction towards right-handedness and because of overrating of items, which are not significant for innate handedness. The effect of the social norm, which favors the preferred use of the right hand and leads to suppression of left hand use, is confirmed by several results.

First, the frequency of left-handedness and left hand writing is subject to cultural beliefs and attitudes. Left hand preference emerges more often in permissive cultures than in harsher cultures (Dawson, 1972, 1977; Ida & Mandal, 2003; Perelle & Ehrman, 1994; Shimizu & Endo, 1983; Teng et al., 1976, 1979).

Second, the decreasing pressure to switch writing hand increases the prevalence of apparent left-handedness in Western societies. Studies in several countries demonstrated increasing left-handedness in later born participants (Brackenridge, 1981; Dahmen & Fagard, 2005; Ellis et al., 1988; Fleminger et al., 1977; Gilbert & Wysocki, 1992; Hugdahl et al., 1993).

Third, right shift attempts are very usual: Teng et al. (1976) reported attempts of switching hand use, not only for writing hand but generally for manual activities, for 18% of all participants, irrespective whether they were classified as left- or right-handers (cf. Porac et al., 1986; Searleman & Porac, 2001, 2003). In Ivory Coast and Sudan pressure against left hand use especially for eating but also for other manual activities is common (de Agostini et al., 1997). In Ivory Coast 79% of left-handers and 16% of right-handers experienced such influence. The figures for Sudan were slightly lower (53% and 8%).

Fourth, left-handedness is scorned: Zverev (2006) reported that 75% of respondents of a survey in Malawi considered left-hand use negatively and 87.6% supported forcing left-handers to change hand preference. Their main reasons are: The left hand is less powerful than the right one, the left hand is less skilled than the right one, and the left hand is dirtier than the right one.

Altogether, an increasing incidence of left-handedness is observable. This can be understood as a consequence of a growing acceptance of earlier disapproved behavior.

Beside the social norm there are four other causes as to why questionnaires do not achieve what they claim to. First, there is a questionnaire bias. For well known and obvious reasons (e.g., switching or tool design) left-handers perform some tasks (writing or using scissors) more often with the right hand than other activities. Such items reduce the score for left-handedness even when evidence lacks that real hand preference is less strong in left-handers than in right-handers. Questionnaires, which are presumably biased, show that left-handers are less lateralized.[2] Second, a self-image of handedness may lead to some bias when answering questionnaire items. It is conceivable that participants give the answer "right" on an item, even when they do not really know how they perform it, as they write with the right hand and understand themselves as right-handed. Third, some items, especially items in reverse scoring (Crovitz & Zener, 1962; Provins et al., 1982), may mislead inattentive participants, who do not mark the correct answer but the self-evident answer "right". Steenhuis et al. (1990) reported that very few participants answered such questions in a nonanticipated manner. Bryden (1977, 1982) found that some of the reverse scored items from the Crovitz and Zener questionnaire loaded in a factor analysis on a single factor, and so assumed that this result was a consequence of inattentiveness, and concluded that "the items seem only to lead to enough confusion to make their value dubious" (Bryden, 1982, p. 163). Fourth, participants may be uncertain how to understand questionnaire items and therefore give incorrect answers regarding hand preference. Low test-retest reliability between 0.39 and 0.63 for 15 of 31 items point to the problem that participants are sometimes uncertain of what to indicate in a questionnaire and therefore make errors (Steenhuis et al.).

[2] Harris (1992, pp. 154-155) also reported some social and environmental influences, which could be the reason that left-handers are less lateralized than right-handers.

### 2.2.6 Better Items for Testing Handedness

After the above considerations what questionnaires really measure, a different approach of how to measure handedness is presented. Based on a broader concept of handedness and the idea that handedness is innate, it is the first task of research to distinguish between innate and instructed features of handedness and to develop methods, which record both effects separately. Therefore, it is an essential condition that items in a handedness questionnaire or test should not comprise of activities, which are controlled and instructed by the social environment or are subject to a social norm. It would be better to have activities, which are performed in a manner that is found and developed by each individual on its own. To achieve a high validity it is important to verify that left- or right-handed performance of an item is not by chance but is influenced by innate handedness. For example, the data of my own experiments suggest that the participants' arm folding pattern is independent from their handedness: From 112 self-defined right-handers and RHWs (of whom some are probably unrecognized SLHs) 57% put the left forearm above and in front of the right. The assumption that each of the two possible arm folding positions indicates either left-handedness or right-handedness cannot be confirmed because LHWs and few switched but self-defined left-handers ($n = 94$) fold their arms in a comparable way as RHWs. The left forearm is in front of the right in 55% of them.[3]

The demanded new testing methods should not include tasks, which are similar to each other like writing, drawing, sewing, or using tweezers, but should contain different activities or use different objects: Clapping hands, broom, vacuum cleaner (on which side), axe, opening a bottle, sitting cross-legged, putting on a T-Shirt (which arm firstly enters a sleeve), children climbing up stairs (infants initial step onto each individual step on a staircase is typically with the same leg), or stepping into a sack or pants. It is unlikely that anyone ever made an effort to show someone else how to perform these activities never mind to teach them a particular sidedness.

Traditional questionnaires sometimes contain items like an axe and a bat (Steenhuis & Bryden, 1989) or a broom and a rake (Oldfield, 1971). These items provide results, which are deviating from the prevailing result of a 90% right-hand preference. Additionally, a

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[3]For both groups (RHWs or rather LHWs including a few SLHs) the hypothesis that 50% of the participants prefer having the left forearm above and in front of the right forearm and the other 50% of them prefer having the left forearm in the back of the right forearm cannot be rejected statistically (for RHWs: $\chi^2(1,\ N = 112) = 2.29,\ p \approx 0.13$; for LHWs and switched but self-defined left-handers: $\chi^2(1,\ N = 94) = 1.06,\ p \approx 0.30$). Possibly this item is controlled by a sociocultural bias. Therefore both LHWs and RHWs may have a weak preference for one arm folding version.

handedness test by Davison (1948) points at some interesting tasks like wiping dishes, opening a book, or using a shovel.

### 2.2.7 Alternative Methodology of Testing

Beyond the discussion of current tests and questionnaires and their weaknesses and proposals for an alternative way of testing, there is a methodological approach for a classification and evaluation of handedness tests and questionnaires. McGrew and Marchant (1994) presented some criteria to verify how general or specific the method and framework of a test is as part of conceptual considerations for a methodology of testing. The idea of an analysis of methods and frameworks stems originally from an analysis of methods in the research of laterality of function in apes (Marchant & McGrew, 1991) and was transferred to the research on human handedness. Marchant and McGrew defined eight variables (p. 428) for the analysis of laterality of function: Function (which organs, i.e., hands, arms, or feet, are observed), context (captive or wild animals), sample (number of subjects), age of subjects, task (induced or spontaneous), number of tasks, trials (number of trials per subject per task), and complexity (degree of difficulty or intellectual demand of tasks).

The intention of the variable definition is to evolve criteria for an assessment, whether tests and questionnaires in human handedness research are focused on a restricted concept of handedness and are limited regarding the framework, or, whether a universal measure of hand use, of limb use, or more general, of body movement is the aim of a test or questionnaire. Based on four variables (number, age, task, and complexity) McGrew and Marchant (1994) rated some selected model studies as to whether methods and frameworks allow a generalization of the results and concluded: (a) Only few tasks were used; (b) children (immature participants) were often tested what may restrict the generalizability; (c) induced tasks were often and self-reports were rarely used, but never spontaneous acts; and (d) “the measures or tasks chosen were not a random sample of manual activity.... All studies in this limited sample used measures only of object manipulation, and other hand usage such as gestures or mannerism was ignored” (McGrew & Marchant, p. 181).

Beside the problem of reliability due to of missing retests they determined that “any or all of these four factors present potential problems of validity of measures.... Thus, in contrast to what textbooks and other secondary sources assert, neither the uniqueness nor the universality of human handedness is yet proven” (McGrew & Marchant, 1994, p.

181). Finally, they suggested that manual behavior from everyday life like communicatory gestures, mannerisms, and habitual self-directed acts should be included in new tests.

The conceptual considerations on handedness testing were put to practice to a certain degree by Marchant et al. (1995) who analyzed cinematic material filmed in three traditional preliterate societies in Africa (G/wi San of Botswana and Himba of Namibia) and South America (Yanomamö of Venezuela). As the material already existed the researchers could not make any decisions concerning the test methods and the eight variables defined by Marchant and McGrew (1991). Nevertheless, with regard to some of the variables the material offered good preconditions according to the criteria introduced by McGrew and Marchant (1994). All activities were spontaneous or at least induced by tribe fellows and were not prompted by the researchers. In principle the material contains observations for lower and upper limbs. Marchant et al. classified all observations for arms, hand, and feet but finally analyzed only a part of the data. For other variables such as sample, age, number of tasks, number of trials, and complexity some restrictions existed due to the available film material. The material showed a wide range of everyday motor activities performed spontaneously and unstaged. The manual activities of 109 individuals were arranged in 61 groups of defined limb movements. From all coded activities only the one-hand acts and two-hand acts with a dominant hand were analyzed.

One result of the analysis was already presented earlier: Using tools is not the normal case of hand use (only 14% of all unimanual acts are with tools), but a special case, although typical questionnaires suggest the opposite. For all individuals and all manual activities the pooled data indicated that nontool use is performed slightly more often with the right hand (53% to 55% of all acts, with minor differences for the three societies) than with the left hand (45% to 47% of all acts). Tool use was performed more often right-handed (79% to 91%).[4]

Marchant et al. (1995) annotated that these pooled data may be misleading, because a 50:50 distribution of hand activities could have two different causes. Either, a population could consist of 50% left-handed and 50% right-handed individuals, which are performing all activities with their preferred hand. Or, all individuals are equal and indifferent, and are performing half of all activities with the right hand and half of all with the left hand.

[4] The relevance of the result for tool use is questionable for two reasons. First, tool use is instructed and it cannot be ruled out that hand preference for tool use is also instructed. Second, even in traditional preliterate cultures tools may be manufactured for use with one - usually the right - hand like in western cultures. Both could be the reason for the fact that in these three traditional cultures, like in the western culture, the right hand is used predominantly for tool use.

To clarify which of these extreme cases is closer to reality, they carried out an analysis of the data on an individual basis. Based on the analysis for nontool use most individuals could not be assigned either to the group of left-handers or to the group of right-handers. Only 3 (of 109) individuals were statistically significantly left-handed and 9 individuals were right-handed. All others were statistically significantly ambilateral or not significantly testable. When handedness was determined by preferential tool use nobody could be classified as left-handed but 24 as right-handed.

For hand use, or at least for nontool use, Marchant et al. (1995) demonstrated that a 10:90 ratio of left- and right-handers does not exist. They explain this disparity between the ethological results and the accepted psychological results on handedness with a simple but convincing argument: "Questionnaire and performance-testing paradigms focus only on a small and selected proportion of manual activities, those to do with tool use, and especially with skilled, fine-motor tool use. This gives an artefactual, biased picture of extreme lateralization" (p. 256). Marchant et al. continued with an explanation of how questionnaires generate biased results:

> It seems likely that this results inadvertently from the procedures for refinements in psychometric testing development. Items, that is, hand-use tasks, may have been retained if they gave clear and clean results, as from precision tool use, while other, messier items were likely largely discarded, e.g. simple object manipulation, gestures. This meant that standard instruments evolved to be specialized measures of tool use, and not generalized measures of overall hand use, and so are likely to be correspondingly misleading. (p. 256)

### 2.2.8 Assessment of Measuring of Handedness

The validity of both research instruments, questionnaires and tests, is at present possibly sacrificed to reliability. Asking participants not only to fill out a questionnaire but also to perform the items (cf. Chapman & Chapman, 1987, p. 181) does not seem to be an appropriate method to assure validity as the items are still the main problem. Rather it were first to make theoretical considerations and empirical research, including comparisons with animal research, to understand what handedness is and second, to demonstrate that questionnaires as well as tests measure the feature *handedness* and not like current questionnaires something that I would call a *tool use index*. Until now research was mostly directed to reliable but invalid instruments, and disregarded many of the above discussed problems.

## 2.3 Discussion of Handedness Theories

The environmental theory stresses the role of learning for the formation of individual hand preference (Hertz, 1909/1960; Perelle et al., 1981; Provins, 1997) and claims that handedness does not have an innate component. This theory is inconsistent with the fact that most left-handed offspring are in families with two right-handed parents (McManus & Bryden, 1992) who hardly influence a child to show a left hand preference. The reverse seems also inaccurate. Offspring of left-handed parents are to a higher degree (20% to 50%) left-handed than offspring in other parental combinations but not at all up to 100% (Annett, 1972, 1974, 1983; Dahmen & Fagard, 2005; McManus & Bryden). These observations suggest that there must be, apart from environmental influences, another cause of handedness especially of left-handedness. The innate part of handedness can be either explained by a genetic model or by the proposed model of a 50:50 random distribution of left- and right-handedness with strong shift attempts towards right-handedness.

The genetic theory (Annett, 1985; McManus, 1985b), which tries to explain the occurrence and frequency of left- and right-handedness, also has its limits, at least when it is understood as an exclusive theory. Some observations (cf. 2.2 *Discussion of Methods and Results of Testing*) suggest that handedness is influenced by learning, by a cultural or social norm, and by social control: First, the frequency of left hand writing (as well as left hand preference in other activities) is increasing in Western societies (Ashton, 1982; Brackenridge, 1981; Fleminger et al., 1977; Gilbert & Wysocki, 1992; Hugdahl et al., 1993; Smart et al., 1980; Spiegler & Yeni-Komshian, 1983). Second, left-handedness is found more often in permissive cultures than in conservative cultures (Dawson, 1972, 1977; Ida & Mandal, 2003; Perelle & Ehrman, 1994; Shimizu & Endo, 1983; Teng et al., 1976, 1979). Third, the incidence of left-handed offspring is higher when the mother is the only left-handed parent, who often raises the child and is probably aware of her own left-handedness and the potential left-handedness of the child, and not when the father is the only left-handed parent (cf. Annett, 1972, p. 348).

The pure genetic theory cannot explain these results. The only possible explanation seems to be that handedness is or at least was switched in left-handers.

Even when it is accepted that left-handers are switched in their preference the genetic theory gets dubious when the frequency of left-handedness is too high. For McManus' (1985b) genetic model a share of 20% left-handers would require that the frequency of the C gene in the population is 40%. Slightly more than 25% left-handers would imply that the C gene is more frequent than the D gene. In this case it would be surprising that the

C gene is more frequent, however the less frequent gene D causes the population to be by majority right-handed. Given that a left writing hand emerges in frequencies between 14% and 23% in different samples and countries (Dahmen & Fagard, 2005; Marrion, 1986; Smart et al., 1980) this consideration does not seem as absurd as it did decades ago when left-handedness was very rare with frequencies between 2% and 5%. Anyway, high and increasing shares of left-handers in Western populations are a challenge for the theory and ask for some explanation of how this could match with McManus' genetic model.

Estimations based on the framework of the genetic theory face another problem: For obtaining unbiased results it would be necessary to separate the impact of innate handedness and the impact of influence and instruction. This was not considered and biased data were used in the previous research. Theory, data, and results are therefore inconsistent. Which data should be used for computing the parameters of the model (the frequency of the C and D gene) remains unclear, and also what the true parameter values would be if there was no social pressure on left-handers. Finally, something exists like heredity in the context of right- and left-handedness. However, the transmission is not genetic but rather sociocultural. Right-handed parents instruct their children more often towards a right hand preference than parents with at least one left-handed parent.

Although it would now be appropriate, I do not wish to discuss the theory of PLH in this subsection but want to refer to Beaton (2003, pp. 125-129) who listed some shortcomings of this theory. In the next section there will be a discussion of how symptoms, which are currently seen as symptoms of PLH, can be understood according to the new model of handedness.

The assessment of the environmental and the genetic model has shown that both theories are disputable and cannot completely explain handedness data and particularly changes of the frequency of handedness during the 20th century. Handedness as it is currently measured and perceived seems to be both innate and influenced and the occurrence of left-handedness depends on the attitude towards left-handedness. The previous models seem to be driven by data and are not based on sufficient theoretical and experimental research, which should include animal research. The previous data, however, should also be considered critical as they rely on the disputable application of questionnaires. A new approach in handedness research is necessary and validity should have priority. The differentiation of the effects of innate handedness and environmental influence should be another important aim of a new theory and a new experimental method.

# 3 Alternative Handedness Model

Based on the considerations and results of the above discussion a new alternative model of handedness shall be presented. As the predominance of right-handedness is proposed to be not innate but learned, instructed, and limited to tool use, a requirement or necessity to put forward an elaborate model, which explains this predominance, does not exist. I think that a model of innate handedness must be simple and should not propose differences between humans, nonhuman primates, and other mammals when a cause and evidence from an evolutionary or from other points of view (e.g., an embryologic point of view) is lacking. The results of previous experimental research have a limited value, are invalid, and do not provide a sufficient cause to require different models for human and animal handedness. Additionally, the new model should explain how and under which conditions the innate handedness in humans and animals can be influenced.

In this section four questions should be answered. First, what is an appropriate model of innate handedness, which is based on the generally accepted findings of genetic and neurological research? Second, how is handedness distributed? Third, are factors like influence, learning, and social norm an adequate explanation that a 10:90 ratio of left- and right-handers can be observed for preferential tool use despite the proposed innate 50:50 ratio? Fourth, which differences between left-handers, right-handers, and SLHs exist and can be observed, and do these differences indicate a switched hand preference in about 40% of the population?

For certain reasons I do not want to discuss the question, as to why hand preference in humans is shifted in almost all cultures to the right. First, this would inevitably lead to speculations about belief, myths, and legends concerning handedness and the superiority of one side of the human body. Even in ancient times humans were surely aware that the heart is on the left side. It remains open whether early humans made inferences regarding hand preference or hand superiority based on this knowledge, but it might be possible. Second, the observation of functional asymmetries of today's humans seems to me more important and meaningful than doing research on handedness of Neolithic or even earlier humans or rather simply speculating about their handedness. Third, since humans established institutions like states and were waging war, they needed coordination in matters of handedness and laterality. The hoplites of the Greek phalanx had to have the spear in the same (right) hand and the shield in the other hand. The cavalry soldiers usually mounted and dismounted their horses on the same (left) side. The stone slingers with a shepherd's sling, a very old weapon possibly invented in Upper Paleolithic, standing side by side in a battle had to throw the stones with the same (probably right) hand to avoid mutual disturbances or damages in their own formation. We do not know whether predominant right-handedness of humankind is a cause or a consequence of the actual chosen rule of coordination.

The first subsection (3.1 *What is Innate on Individual and Species Level?*) of the following three subsections deals with features of innate handedness:[5] (a) Asymmetry and directionality of the brain; (b) distribution and degree of handedness; (c) handedness in animal species; (d) human handedness and lateralization of speech; and (e) sidedness, an extended concept of handedness. In the second subsection (3.2 *Switching Handedness, Different Degrees of Influence, and Consequences*) aspects of influencing and switching handedness and the consequences are discussed: (a) Individual and species dependent aptitude to be instructed and influenced and external sociocultural factors, (b) influencing handedness of animals, (c) switching handedness in humans, (d) prevalence of left-handedness in clinical patients, and (e) psychological consequences of switching left-handers. The third and last subsection (3.3 *Differences in Left-Handers, Switched Left-Handers, and Right-Handers*) focuses on determinable differences between left-handers, right-handers, and SLHs regarding psychological characteristics and related neuronal and physiological features: (a) Motor skills, (b) intellectual performance and spatial ability, (c) speech impairment, (d) personality traits, (e) scanning direction in visual perception and drawing direction, (f) hemispheric asymmetry of neuronal activity, and (g) physiological measures.

## 3.1 What is Innate on Individual and Species Level?

I consider handedness to be based on innate asymmetric structures of the central nervous system especially of the brain. As particular functions are lateralized in one of the hemispheres, the brain is asymmetric and has a specific directional structure in almost all individuals of a species.

The asymmetry of the animal or human body including the cerebral structure is inherited by genes. Despite its three dimensional helix structure the DNA can only transfer information on a string of base pairs. The impossibility to code spatial information on DNA leads to the conclusion that "genes themselves may well be *left-right agnosic*: able to produce asymmetries, but unable to code for the direction of those asymmetries"

[5] The structuring of the three subsections shows some minor differences compared to the following outline of the content.

(Morgan, 1977, p. 173). Further Morgan derives:

> To say that there is a "factor" that induces right-handedness in the majority of people is undoubtedly correct. But the data do not show that it is a *genetic* factor; it is much more likely that it is a nongenetic factor, as in the case of the heart. (p. 188)

Other researchers (Collins, 1977; Morgan & Corballis, 1978) also propose that the direction of handedness is not under genetic control. Nevertheless, there seems to be a common mechanism that coordinates asymmetries of the body like the position of heart, liver, and lung lobes.

The idea of a nongenetic brain directionality is one source for elements of the model of brain asymmetry and handedness. Another source is animal research. Some of the features (innate lateral preference, U-shaped distribution, and noninheritance of handedness) of the following model have been demonstrated by Collins (1968, 1969, 1975) for mice and by Peterson (1934) for rats. Situs inversus in mice (Hummel & Chapman, 1959; Layton, 1976) is an example for an asymmetry, which is not evoked by a coded directionality but occurs randomly with a 50:50 ratio in two mirror reversed states.

The incidence of discordant handedness in monozygotic twins indicates as well that brain directionality is nongenetic. In monozygotic twins left-handedness occurs more often than in general population but the majority of twins is nonetheless right-handed (Orlebeke, Knol, Koopmans, Boomsma, & Bleker, 1996; Rife, 1939, 1940; P. T. Wilson & Jones, 1932). The increased left-handedness of monozygotic and dizygotic twins compared to singletons appears to be a problem for the pure genetic models suggested by Annett (1985) and McManus (1985b) as these models do not disclose a reason that the left-handedness causing gene ($rs^-$ or C) is more frequent in monozygotic twins.

### 3.1.1 Model of Asymmetry and Direction of Asymmetry

The model of asymmetry and directionality of the brain is made up of four elements:

1. Brain asymmetry is innate and under genetic control (Collins 1977, 1985; Corballis & Morgan, 1978). The fact of cerebral asymmetry is well known and accepted. Brain functions are lateralized in specific brain regions (cf. Kolb & Whishaw, 2003). For the further argumentation and for the proposed theory of handedness this functional cerebral asymmetry is of much more interest than anatomical differences of the hemispheres.

2. The functional representation of handedness or hand dominance is mirror reversed in left- and right-handers. In left-handers the right hemisphere of the brain is dominant for hand motor activities, in right-handers the left hemisphere. This proposal is contrary to the common view of lateralization, as, for example Harris (1992) claims that "for cerebral organization ... left-handers are neither the same nor the mirror-reverse of right-handers" (p. 194). It follows from brain asymmetry and unilateral cerebral representation of handedness that handedness is a unidimensional feature. Research that reports multidimensional handedness is either disturbed by switching of handedness or by inappropriate methods of measuring handedness. Any deviation of functional lateralization of handedness from the innate mirror reversed structure is either caused by environmental influences (switching handedness) in a right-handed world or by brain lesions.

3. Asymmetry is determined in a random process. (This thesis is probably seen as most critical.) Collins (1985) understands it as an "'asymmetry lottery' in which the directions of asymmetry emerge as the outcomes of seemingly random processes" (p. 64). As a consequence of this process, which is a fair and dichotomous random process, handedness is an innate feature with left- and right-handedness as two states. In terms of population, handedness does not show a right-handed majority but a ratio of 50:50 of left- and right-handers.[6] As most individuals are explicitly lateralized and are either right-handed or left-handed the distribution is U-shaped with only a small group of individuals, which cannot be assigned to one group. The ratio of left- and right-handed individuals is equal in both sexes, but the U-shaped distributions for the sexes may differ in shape because of a stronger lateralization of one sex. A further consequence of the random process is that handedness of an individual (as an innate characteristic) is independent of the handedness of all ancestors.

4. Handedness is a stable and innate characteristic, which is based on the structure of the central nervous system. Peterson (1931, 1934) showed that paw preference in rats is stable when animals are retested and brain function for handedness is

[6] The thesis that between 30% and 50% of humans are left-handers (instead of the idea that there is a predominant majority of right-handedness with a 10:90 ratio of left- and right-handers), was presented at least four times in the last few decades by authors publishing in German or with German translations of their work (Caliezi, 1983; Rett et al., 1973; Sattler, 2000; Sovák, 1968). Only two authors, Rett et al. and Sovák, provided some empirical results to support their suggestions.

> lateralized in the front area of the contralateral hemisphere. Lesions of the motor area in the dominant hemisphere of less than 4% of the size of one hemisphere can cause a transfer in the preferential use of paws (Peterson, 1934). Collins (1968, 1970) tested the consistency of paw preference in mice and demonstrated that handedness is a very stable feature. Nevertheless, handedness is switchable. Either through training or lesions. The ability of the brain to adapt to both influences indicates its immense plasticity.

The current theory of human handedness proposes either a genetic factor, which causes the preponderance of right-handedness (Annett, 1985; McManus, 1985b), or a nongenetic influence, which is passed on by something like a molecular structure or a maturational gradient (Brown & Wolpert, 1990; Morgan, 1977, 1978, 1991; Morgan & Corballis, 1978; Wolpert, 2005). Either factor causes a dominant left cerebral hemisphere.

As there is a 50:50 ratio of left- and right-handed individuals in mammals like mice (Collins, 1968, 1969, 1970; for replications see Betancur, Neveu, & Le Moal, 1991; Biddle, Coffaro, Ziehr, & Eales, 1993; Signore, Nosten-Bertrand, Chaoui, Roubertoux, Marchaland, & Perez-Diaz, 1991) and rats (Peterson, 1934) the genetic and nongenetic theories fail to explain why and how such a difference between humans and other mammals should exist. It seems likely that cerebral asymmetry is induced in embryonic development and this developmental phase is similar for all mammals. I suggest that the directionality of the cerebral mechanism for handedness is one of the common features in all mammals. This directionality is determined for each individual in a random nongenetic process although the existence of asymmetry is genetically coded.

Instead of a gradient, which causes a special outcome on population level, I propose a theory with a left-right gradient and two random processes, which are independent from each other, in embryonic development. One process determines a particular visceral structure (usually situs solitus) and the other an asymmetric cerebral organization.

### 3.1.2 Situs Inversus in Mice — An Analogy

The case of situs inversus of viscera in mice (Hummel & Chapman, 1959; Layton, 1976) is an analogy to the asymmetric model of innate handedness. Situs inversus is evoked by an autosomal recessive gene (symbol *iv*) and occurred in 50% of homozygous (*iv/iv*) animals. The other 50% of the animals showed situs solitus. Parental situs does not influence the situs of offspring. Hummel and Chapman reported that for 58% and Layton reported that for 74% of animals there was a normal relationship, position, and shape of all asymmetrical structures. In the others heterotaxia was found. Despite situs inversus the asymmetric structure of viscera seems, at least to a certain degree, to be coded in *iv/iv* mice. Directionality of visceral structure is not coded and is random with a ratio of 50:50 on population level. The mechanism that organizes viscera with reference to the left-right structure of the embryo is obviously missing in *iv/iv* mice.

McCarthy and Brown (1998) demonstrated that chemical treatment of rat embryos can induce situs inversus and other abnormal development of left-right asymmetries. However, the incidence of abnormalities did not significantly exceed 50%. The sensitive period for the treatment was up to the early headfold stage. Therefore, the sensitive period was before the embryo showed first morphologic asymmetry. Otherwise from the late headfold stage onwards treatment was ineffective. Thus, the sensitive period ended before the embryo showed morphologic asymmetry by means of the primitive streak, which implies the formation of the dorsoventral, the anteroposterior, and the left-right axis.[7] As the axis were not defined and developed in the sensitive period they obviously were not taken into account for the asymmetric development of viscera. Therefore, the treatment did not cause a change of the left-right axis but induced the ineffectiveness of a mechanism, which distinguishes left from right. The directionality of the asymmetric visceral structure of the embryo developed randomly and up to 50% of individuals had an inverted visceral situs.

In the same way I would apprehend the occurrence of situs inversus in *iv/iv* mice. Asymmetry is coded and the information as to which side is left and right, is not missing but it is impossible to distinguish left from right.

A complete reversal of left-right asymmetry in mice reported Yokoyama, Copeland, Jenkins, Montgomery, Elder, and Overbeek (1993). They generated a recessive mutation that causes situs inversus in 100% of the homozygous (*inv/inv*) animals. In this mutation the mechanism, which organizes the directionality of the viscera of an embryo, is not missing but works in a mirror reversed manner.

Situs inversus in *iv/iv* mice is an example how the cerebral mechanism for handedness could be understood. Nevertheless, it remains unanswered why cerebral organization is random. Two development processes are conceivable: (a) The lack of a left-right reference

[7] A left-right axis already exists when two axis in the embryo are established. Once the dorsoventral axis and the anteroposterior axis are apparent, the remaining axis has to be the left-right axis and the left and right side of the body are defined. The dorsoventral and the anteroposterior axis are defined when the primitive streak on the surface of the epiblast of the germ disc appears (in humans after approximately 14 days of embryonic development; cf. Sadler, 1995).

at the stage of simultaneous development of the directionality of the central nervous system and of the three axis of the embryo makes the control of directionality impossible. In this case the directionality of both features, the structure of the central nervous system and the asymmetry of the germ disc, is determined by a common underlying random mechanism. (b) Despite the existence of a left-right reference both directionality of the brain and handedness are random and independent from the morphologic structure of the embryo. Handedness might be determined randomly because it represents an evolutionary advantage when the ratio of left- and right-handers is always 50:50.

### 3.1.3 Inheritance of the Degree of Lateralization

Beside the asymmetry of the brain and its random directionality, which determines handedness, there are other features of handedness: The degree of lateralization or the extent of motor skill. The U-shaped distribution of handedness in mice (Collins, 1968, 1969) points at different strengths of paw preference. By applying selective breeding Collins (1985, 1991) showed that the strength of handedness is innate. After 10 generations of selective breeding two lines were established, a HI line of strongly lateralized mice with a clear preference for either the left or the right paw, and a LO line with a weak preference for either paw. From generations 11 to 27 the selection was relaxed and mating was random within each line. In generation 28 to 30 breeding was reimpressed and all animals were tested for handedness (Collins, 1991). The divergence in degree of lateralization between both lines remained during the period of relaxed selection. Although the direction of handedness is not inherited and about 50% of mice in both lines (HI and LO) were left- and right-handed in each generation this result demonstrates that the degree of lateralization is inherited and genetic.

Other research groups (Betancur et al., 1991; Biddle et al. 1993; Signore, Chaoui, Nosten-Bertrand, Perez-Diaz, & Marchaland, 1991) reported differences for the degree of lateralization of paw preference for several strains of the mouse. Selective breeding was not applied in these experiments but different inbred strains were selected. A strong lateralization has been demonstrated for some strains whereas other strains had weak paw preference. For most strains the ratio of left- and right-handed mice did not deviate significantly from the 50:50 ratio.

Westergaard and Suomi (1996) found evidence for different strengths of handedness in species in an experiment with two species of monkeys. Plastic tubes with food on the inside were presented to tufted capuchins ($N = 45$) and rhesus macaques ($N = 55$). When extracting the food, mostly with the index finger of one hand, capuchins showed a greater strength of hand preference than rhesus macaques. Westergaard, Kuhn, and Suomi (1998) reported different absolute strength of handedness for 10 primate species (including humans) in two tasks, where participants had to reach for food from quadrupedal and bipedal posture.

Compared to the research on mice, a detailed analysis of strength of handedness in weakly and strongly lateralized populations is missing for humans. Nevertheless, I expect that the strength of lateralization is also genetically controlled. The motor skill of the dominant hand or limb compared to the nondominant, the aptitude to understand and obey instructions, the intellectual achievement, and the individual motor performance may be some of the diverse features, which should be studied to understand the degree of handedness and the inheritance of the degree of handedness. Additionally, further comparisons of species may confirm that the ability of an individual to change hand preference is species dependent.

### 3.1.4 Handedness in Animals: Innate Preference, Distribution, and Noninheritance

The main concern of this thesis is on human handedness, but the manifestation of innate handedness in animals should not remain unnoticed. Particularly for primates, the methods of determining handedness, the theory, and the results are in dispute. One cause may be that primates are more weakly lateralized than other mammals and therefore the results are less clear. Warren (1980) states that a 90% preference of an individual for either hand/paw, left or right, can be found more often in mice and cats than in nonhuman primates. Another cause could be that the idea of genetic right-handedness is transferred from humans to nonhuman primates, especially to the great apes.

For no other species is the knowledge about handedness so precise except for mice (Collins, 1968, 1969, 1970, 1975, 1985, 1988, 1991). To assure genetic uniformity of the subjects Collins (1968, 1969) used mainly mice from highly inbred strains. The testing environment was a plastic box with a horizontally fixed feeding tube, which was filled with food and could be equally reached by a mouse with either forepaw. After deprivation of food for 24 hours mice were placed in this box and the first 50 reaches for food were observed and recorded. On population level nearly half of all paw reaches were carried out evenly with either the left or the right paw (Collins, 1968). On an individual level a high proportion (58% of all mice) were explicitly lateralized and were either strongly right-handed or strongly left-handed (Collins, 1969). Therefore, the distribution of paw reaches was neither binomial nor bell shaped but U-shaped. Only few individuals were classified as ambilateral and the feature handedness can be seen as nearly dichotomous. Female mice demonstrated a stronger lateralization than male mice (Collins, 1985; cf. Betancur et al., 1991; Signore, Chaoui, et al., 1991; Signore, Nosten-Bertrand, et al., 1991). Retests with some mice confirmed a permanent and reliable handedness (Collins, 1968, cf. Signore, Nosten-Bertrand, et al.).

Neither a parental effect on handedness of offspring nor a connection of handedness and sex of offspring was found in an experiment with selected mating of left- and right-handed mice for three generations (Collins, 1969). In all three generations and regardless of the handedness combinations of dam and sire (L-L, R-L, L-R, R-R) the offspring were about half sinistral and half dextral. As maximal variation in lateralization existed in an inbreed population with minimal genetic variance, Collins (1968, p. 12) suggested that a particular specification of handedness (i.e., left-handedness or right-handedness) is not genetically determined.

Another experiment studied the consequences of environmental influence on handedness and pointed out thereby that handedness is innate, although it is not genetically inherited (Collins, 1975; additional details in Collins, 1977). In the first phase of the experiment mice were tested twice in a biased environment where food was easier to reach with one paw, because the feeding tube was placed either next to the left wall or next to the right wall of the testing cubicle. Mice were randomly allocated to one of the experimental environments (L-world and R-world). In the biased world most mice behaved like the bias forced them to (left paw reach in L-world and right paw reach in R-world), but a fraction of 13.5% in the first and 9.7% in the second test demonstrated a paw preference differing from the bias. Male mice showed stronger conformity to the biased world than females. In a second phase of the experiment all mice were forced to adapt to an antiworld with a reverse bias, compared to the previous phase of the experiment (test sequences L-L-R or R-R-L). In this phase, two groups (A and B) of nearly the same size (108:106) were identified: Subjects in one group (group A) behaved in accordance with the new bias, irrespective whether a left or right bias existed, and reached at least in 26 of 50 attempts for food with the favored paw. The second group (group B) reached more often (26 to 50 times) for food with the nonfavored paw despite the new bias in this phase. The comparison of the two groups, which showed a different behavior in the second phase, regarding their paw preference in the first phase, led to an impressive result.

Both groups were not only differing in the second phase but even in the first phase: Mice from group B behaved in the first test of the first phase almost completely according to the world bias and in the second test behaved completely according to the world bias, as they used the left paw in the L-world and the right paw in the R-world. Mice from group A, preferring the bias in the second phase, resisted to the first bias and used frequently the nonfavored paw in the first phase. Nearly all nonconformist mice were in group A.

It can be concluded from Collins' (1975) experiment that the paw preference of the groups should not have differed significantly in the first phase if paw preference had been learned. However, as paw preference for both groups, which were separated in the second phase, differed in the first phase, it must be innate in some way although it is nongenetic, as we have seen above.

Signore, Nosten-Bertrand, et al. (1991) analyzed the paw entry sequences for 306 mice. Between 70% and 90% of all mice used their preferred paw on each of 50 reaches. For the first paw reach, 81% of the females and 75% of the males were acting with the preferred paw and this percentage increased only slightly from the 1st to the 50th paw reach. This result confirms as well that paw preference should be understood as innate and not as learned or acquired.

It was also demonstrated in the biased world with mice of different degree of lateralization (HI and LO) that the degree of handedness is innate and can be different in lines (Collins, 1991). After one unbiased test all mice were tested twice in an environment with a bias opposing to their handedness (test sequence U-L-L for right-handed mice and U-R-R for left-handed mice). HI line mice were more lateralized in the unbiased world, resisted the biased world, and used their preferred paw for feeding even when it was uncomfortable. Mice from the LO line behaved less lateralized in the unbiased world and conformed more to the demands of a biased world.

The results from the biased world experiments and other findings (U-shaped distribution and noninheritance of handedness) by Collins (1968, 1969, 1975, 1991) are sometimes summarized with terms like learning, sociocultural influence, or environmental factors (e.g., Provins, 1997; Tambs et al., 1987). However, Collins showed the exact opposite. Handedness is innate in each individual, although the strength can vary from one individual to another or in lines (HI and LO). In Collins' (1977) own words, "These findings are inconsistent with the view that mice learn their handedness in the paw preference tests. The analyses are consistent with the view that mice arrive for paw preference testing with an already established sense of lateral specialization" (p. 144).

Unfortunately results on handedness of *iv/iv* mice (Hummel & Chapman, 1959; Layton, 1976) are not available. If handedness distribution were U-shaped in situs inversus mice, as well as in situs solitus mice, like in other mouse strains, it would demonstrate that handedness and situs are determined in two independent processes. Clones of mice (or other animals) could also verify that handedness is not inherited by genes but is somehow based on an innate disposition.

For rats, the results on handedness are not as precise as for mice but point in the same direction. Despite a majority of 52% left-handed rats in one test ($N = 120$) Peterson (1934) presumed equal numbers of left- and right-handed individuals. In an experiment on inheritance left-handed, right-handed, and ambidextrous rats were crossed in various combinations. The parents' handedness did not influence the handedness of the offspring. Offspring were 46% right-handed and 43% left-handed. Altogether, it seems that handedness in rats is nearly dichotomous with a ratio of 50:50 of left- and right-handers and a U-shaped distribution with a small minority of individuals classified as ambidextrous. Handedness was stable in 90% of 60 rats, which were retested from 6 to 19 times on different days. Handedness in rats is innate and dominant paw preference is functionally represented in the front area of the contralateral hemisphere. Brains of left- and right-handed rats are mirror reversed regarding the cerebral lateralization of handedness as lesions of the contralateral hemisphere can change handedness, when the relevant area is destroyed (Peterson, 1931, 1934).

A nonsignificant majority of right handed rats was also reported by Yoshioka (1930). Out of 100 rats 50 were right-handed, 45 were left-handed, and 5 were ambidextrous. He found also a remarkable relationship between handedness and length of bones. Right-handed rats had either equal length of right and left bones in their arms or longer right bones. For left-handers it was the opposite (equal length or longer left bones). As discrimination between cause and consequence is not possible it remains unclear whether the length of bones is an indicator for handedness or vice versa. Tsai and Maurer (1930) reported from their experiment 51% right-handedness and 31% left-handedness in rats (N=108). The whole group and male rats were statistically significantly right-handed.

There is still a debate whether several species of greater apes, mainly our closest relatives chimpanzee and bonobo, show a majority of right-handedness on population level or whether hand preference is symmetrically distributed with equal numbers of left- and right-handed individuals (Hopkins, 1999; Hopkins, 2006; Hopkins & Cantalupo, 2003; Hopkins & Cantalupo, 2005; Marchant & McGrew, 1991; McGrew & Marchant, 1997;

Palmer, 2002). This debate could serve as a good guideline for prospective research on human handedness, as different opinions on statistical and measurement issues and also on methodology are supported and discussed. Such a debate is still missing for the most part in research on humans.

Suggestions by Marchant and McGrew (1991) on methods and frameworks for a classification and evaluation of handedness measurements and a definition of eight variables for the analysis of laterality of function were already presented above (cf. 2.2.7 *Alternative Methodology of Testing*). Out of 241 data-sets of published studies on nonhuman primate handedness McGrew and Marchant (1997) selected on the basis of seven criteria suitable data-sets for a meta-analysis. The requirements were of statistical manner (independence of data points, trials per subject, and number of subjects) and also took into consideration the age of the animals, behavioral category, availability of raw or derived data, and species. Setting (wild or captive) was not a cause of exclusion.

Additionally, McGrew and Marchant (1997) presented a classification system for different distributions of handedness on population level. At first all individuals are assigned to one of five groups (always left, significantly left, ambipreferent, significantly right, and always right). In the second step the number of all individuals in each of the five groups is determined and the possible outcome is differentiated in 5 levels. In level 1 the majority of individuals are ambipreferent. In level 2 and 3 most individuals are either significantly or completely lateralized and the distribution of left- and right-handers is symmetric and by chance. In level 4 and 5 most individuals are either significantly or completely lateralized and a majority is either left-handed (level 4a or 5a) or right-handed (level 4b or 5b). According to this scheme human handedness as it is currently understood and determined by using questionnaires is characterized by level 5b. I would suggest that innate handedness as it is proposed in this alternative model corresponds to level 2 and for some tasks to level 3.

Based on the scheme, McGrew and Marchant (1997) analyzed 48 data-sets and assigned each to one of the five levels. For great apes and lesser apes, many studies demonstrated ambipreferent behavior (level 1) or a significant or complete lateralization with symmetric distribution (level 2 and 3). A level 4 or level 5 lateralization, mostly but not completely with a right-handed majority, was found only in a small group of data-sets. Finally, McGrew and Marchant concluded that “nonhuman primate hand function has not been shown to be lateralized at the species level—it is not the norm for any species, task, or setting, and so offers no easy model for the evolution of human handedness”

(p. 201). I agree that nonhuman primates are not lateralized at species level but I do not share the opinion that nonhuman primate hand function is unsuitable in order to derive a model of human handedness from it. Nonhuman primate handedness seems to be a really good model for human handedness.

In one of the first and classical studies on handedness in chimpanzee Finch (1941) reported a level 2 lateralization with 14 left-handed and 11 right-handed animals, which showed strong preference for one hand in more than 80% of all acts. Byrne and Byrne (1991, 1993) observed wild mountain gorillas while processing and eating food. The observed tasks were naturally-acquired and included complex and bimanual actions. As tasks can be performed asymmetrically there are, overall, two lateral reversed forms of the specific processing and eating task. The results demonstrate that most individuals significantly prefer one motor sequence for one task. For most single tasks Byrne and Byrne did not find a trend either towards left-handedness or towards right-handedness on population level. Rather the distribution on task level was U-shaped and nearly symmetric. The studies by Byrne and Byrne (1991, 1993) are signposts for further studies on nonhuman and human primate handedness because animals were observed in natural habitat and were not tested in a laboratory. The tasks were not induced by humans but spontaneous, the tasks were directed towards an aim, and the motoric procedures were originated by the animals on their own. As the food processing techniques comprised of different stages, the complexity and difficulty was higher than in most laboratory tasks.

In contrast to many studies, Hopkins (2006) found in a meta-analysis of published data of studies on great apes a majority of right-handedness in chimpanzees and bonobos, but did not find this for gorillas and orangutans. In wild animals, which were less than 30% of all animals in Hopkins' analysis, a hand preference did not exist on population level. Animals in captivity (zoos and laboratories) demonstrated a preponderance of right-handedness. Hopkins reported an excess of 44% of right-handed individuals compared to left-handed individuals. In all great apes, wild and captive, the ratio of left- and right-handers is 1:1.36. This is significantly lower than in humans (approximately 10:90) when hand preference is determined by questionnaires. It is remarkable that data-sets from Hopkins' institution (Yerkes National Primate Research Center) comprise of more than 40% of all subjects in the meta-analysis and the majority of chimpanzees from this institution are often found to be right-handed.

Palmer (2002) referred to a sample bias in a study by Hopkins (1994). Animals with fewer observations were more right-handed than others (cf. Hopkins & Cantalupo, 2003 for a reply to Palmer). Palmer also reanalyzed data from McGrew and Marchant (1997) and presumed that the results of a few studies, which showed significant right-handedness in chimpanzees, simply arose by chance. Only the result of one study fell substantially outside the 95% confidence interval (Palmer, p. 196).

Hopkins (1999) and Hopkins and Cantalupo (2005) do not generally see a problem with testing primates in experimental situations in captivity, instead of observing them in their natural environment. They rather pled for the laboratory environment for two reasons. First, in captivity greater sample sizes are possible, which leads to greater statistical power (Hopkins & Cantalupo), and second, the variables are under better experimental control (Hopkins). As Hopkins and Cantalupo have the aim to demonstrate a majority of right-handedness they suggest that the measures from spontaneous activities, which are observed in wild chimpanzees, are not sensitive enough. Instead, it is true that "if one wants to determine whether species exhibit population-level handedness, then one needs a measure that is sensitive enough to reliably detect a consistent hand preference at the individual level" (Hopkins & Cantalupo, p. 73).

In almost all previous human handedness research, an elaborate experimental procedure was followed and the alleged sensitive methods were applied. Questionnaires are apparently reliable, but possibly not valid. The risk to sacrifice ecological validity exists anyway when nonhuman primates are tested in an experimental environment. Fortunately apes cannot fill out questionnaires. Otherwise the results from research with great apes might be as poor as from research on human handedness.

For monkeys and prosimians a level 2 was most often the classification in the meta-analysis by McGrew and Marchant (1997), followed by level 1 classification. A level 5 was not assigned to any study and level 3 was rare. Fifteen data-sets were assigned to level 4 (significant lateralization with skewed distribution). Two thirds of them reported left-handedness of the animals. Also Lehman (1993) did not find any clear trend on population level for monkeys when reviewing and summarizing other previous research contributions. Nearly the same number of studies suggested a preponderance of left-handedness or right-handedness or an absence of any trend in either direction.

The analysis by McGrew and Marchant (1997) and a meta-analysis by Papademetriou, Sheu, and Michel (2005) demonstrated that most primate species do not have a population bias either to left- or right-handedness. Both author groups concluded that the present data do not support the *postural origins theory*, which was proposed by MacNeilage, Studdert-Kennedy, and Lindblom (1987). McGrew and Marchant formulated, "The biggest, simplest conclusion is that there is yet no compelling evidence that nonhuman primates are lateralized at the population level" (p. 226), and deduced "If population-level lateralization has not been shown to be characteristic of nonhuman primates, then it does not have to be explained" (p. 226). Papademetriou et al. drew comparable inferences regarding the population bias and the postural origins theory.

On inheritance of handedness only few studies are available. For the great apes Byrne and Byrne (1991) did not find heredity effects in gorillas for mother-offspring, father-offspring, and full sibling pairs. An analysis for chimpanzee and bonobo showed familial effects (Hopkins, 2006). Regarding the strength of handedness a positive correlation between offspring hand preference and hand preference of both sire and dam is reported. The direction of handedness is inherited from mother to offspring, but a significant effect for a father-offspring relationship does not exist. Studies on monkeys also failed to find a familial effect on handedness. Brooker, Lehman, Heimbuch, and Kidd (1981) could neither determine a directional mother-offspring relationship nor a familial effect on strength of preference. Also Watanabe and Kawai (1993) did not demonstrate a significant connection between mother and offspring handedness.

Although a clarification is required as to whether handedness distribution in apes, monkeys, and prosimians is U-shaped, there is strong evidence that many nonhuman primate individuals are consistently lateralized (e.g., Brooker et al., 1981; Byrne & Byrne, 1991, 1993; Finch, 1941; Fletcher & Weghorst, 2005; Lehman, 1978; McGrew, Marchant, Wrangham, & Klein, 1999; Ward, Milliken, Dodson, Stafford, & Wallace, 1990).

### 3.1.5 Human Handedness and Lateralization of Speech

In contrast to animal research very few studies on human handedness report a ratio of 50:50 of left- and right-handers. This is not surprising as human handedness is strongly influenced by culture. In a subsequent part (3.2.2 *Influencing Human Handedness and Consequences for the Distribution*) the impact of influencing and switching handedness on the distribution of human hand preference will be discussed. The mentioned studies with a 50:50 ratio will also be presented in this following part 3.2.2 to make clear that switching is usual but exceptions arise.

In this part, the focus is more on the connection between handedness and lateralization of speech and is not on the distribution of handedness. A relationship between human right-handedness and left-hemispheric cerebral lateralization of speech in most humans is broadly accepted and proposed (Bradshaw & Rogers, 1993; Harris, 1992, McManus

& Bryden, 1992) and has found its way into neuropsychological textbooks (cf. Kolb & Whishaw, 2003). The connection of handedness and lateralization of speech is understood as functionally and anatomically represented in the cerebral organization of the brain.

Two different theories try to explain the evolution of speech and language. According to one theory, speech evolved from a kind of vocalization like nonhuman primates demonstrate (cf. Kolb & Whishaw, 2003). The second theory proposes that a gestural language was the precursor of spoken language (Corballis, 2003, 2004; de Waal, 2003). Although the idea that speech evolved from manual gestures is widely but not universally accepted, the latter theory is more convincing than the first one because of some findings:

First, a sequence of stages of development (from vocalization to gestural language to speech) seems to exist in primates. (a) All primate species use vocalization for communication and most individuals show motor dominance of either side. (b) A gestural language is evolutionary younger than vocalization as it is typical of apes and humans but not of monkeys (de Waal, 2003; Pollick & de Waal, 2007) (c) Speech is exclusively human. Second, in apes (chimpanzees and bonobos) the use of gestures is more flexible than vocal communication, and gestures are, compared to other types of signaling, less context bound (Pollick & de Waal). Furthermore, "gestures seem less closely tied to particular emotions, such as aggression or affiliation, hence possess a more adaptable function" (Pollick & de Waal, p. 8187). Third, gesture production in humans is automatic and seems to be innate and associated with speech. Blind speakers gesture at rates, which are not different from that of sighted persons. They do even so when the audience is known to be blind (Iverson & Goldin-Meadow, 1998).

It is plausible to suspect that gesturing was established in the common ancestor of human, chimpanzee, and bonobo. Lineage and affinity suggest that this ancestor showed a 50:50 distribution of left- and right-handers like other primates. Based on the insights of evolutionary development it is not plausible as to why humans should be the only primate species with an innate handedness distribution, which deviates from the U-shaped distribution with a 50:50 ratio of left- and right-handers.

The ability of the brain to lateralize functions during the evolutionary process (from manual motor dominance to gestural language to speech) was probably another precondition for the development of human language. Therefore, I propose that not only handedness is random with a 50:50 ratio, but also that the lateralization of speech in either the left or the right hemisphere is determined by chance and controlled by the same random process as handedness.

Finally, not only the speech-developed-from-a-gestural language-approach of explaining the evolution of language but also the speech-developed-from-vocalization-approach should have been accompanied by a development of fine motor control in the vocal apparatus (larynx, lips, and tongue) and/or in hands and face. In any case, the connection of lateralization of handedness and lateralization of speech does not seem to be accidental but can be perceived as a consequence of an evolutionary process.

A more general view on evolution of primates demonstrates that their adaptive strategy did not primarily aim at the specialization of the anatomical structure (e.g., weapons like sharp teeth or claws, high speed racer, or enduring runner) but more at increased brain size and learning capacity (Le Gros Clark, 1949). The increasing performance of the brain expressed by intelligence, speech, and self-awareness facilitates the adaptation to living conditions and their changes. The increased brain size and brain capacity might be the reason for both cerebral hemispheres being specialized at specific tasks, but this does not mean that functional tasks are always assigned to the same hemisphere. According to the proposed theory, speech and handedness are therefore lateralized in the same hemisphere but not necessarily in the left one. The research on nonhuman primates supports the interpretation that (a) brain directionality is determined by chance in each individual and (b) asymmetry is genetically inherited for the entire species. Regarding the development of the brain it seems that humans and animals differ only in degree, not in nature.

The lateralization of speech and the cerebral representation of handedness rely on a common random process, but this does not imply that other brain functions are also lateralized by chance. For functions, which are not based on evolutionary older structures of the brain, but that existed before the functions arose, the process could be a different one. Regarding speech, although it is specific for humans, I want to emphasize that it evolved from evolutionary older behavior (e.g., gestural language and motoric dominance), which is common in primates and in other mammals.

The current theory proposes left-hemispheric speech in most right-handers and also in many left-handers and right-hemispheric speech in a minority of left-handers and very few right-handers. But in my understanding of cerebral organization a dissociation of speech and handedness cannot be innate in healthy individuals. Such dissociation can only occur as a consequence of brain lesions or switched handedness.

It should be remarked that the idea of right-hemispheric speech in left-handers was accepted until the 1950s (Goodglass & Quadfasel, 1954; Orton & Travis, 1929; Quadfasel in a contribution to a discussion [Roberts, 1955]). The differing notion that speech is left-hemispheric in left-handers has been proposed since then.

Corresponding to the cerebral organization, just the dominant hand should be used for writing, because speech and the writing hand are then controlled by the same hemisphere. The writing hand of an individual can undoubtedly be switched, but this may have consequences for the processing of speech and other functions of the brain (cf. 3.2.4 *Psychological Consequences of Switching Left-Handers*).

Previous experimental research seems to confirm the theory that speech is left-hemispheric in nearly all right-handers and most left-handers. An often cited study by Rasmussen and Milner (1977) demonstrated for right-handers a strong connection between lateralization of speech and handedness (p. 358). Out of 134 right-handed patients without evidence of a lesion of the left hemisphere 96% had a left-hemispheric and 4% a right-hemispheric speech representation. For left- and mixed-handers the result was not as unambiguous. Seventy percent of 122 patients speech was lateralized in the left hemisphere. Speech was bilateral or right-hemispheric in 15% of each case. These results definitely support the theory of left-hemispheric speech. But in the same study Rasmussen and Milner presented results for patients with clinical evidence of early left-hemispheric lesions (p. 359), and for this group the results are quite different. For 42 right-handers the result is similar to the above but not as clear. Of all right-handers 81% had left-hemispheric speech, 7% bilateral, and 12% right-hemispheric speech. For 92 left- and mixed-handers the result deviated much from the above result. A majority of 53% demonstrated right-hemispheric speech. Bilateral speech had 19% and only 28% showed left-hemispheric speech.

It remains unclear, which of the results come closer to the real distribution of lateralization of speech in left- and right-handers and what causes the difference. If switching handedness exists on such a large extent as I propose, it can be expected that SLHs without a cerebral lesion may show often left-hemispheric or bilateral speech representation. Practiced writing with the right hand is the only reason for this. Nevertheless, I suggest that the right hemisphere of a SLH has at least some minor function in understanding and production of speech. As both hemispheres are intact it could be difficult or impossible to determine whether some persons classified as right-handers are actually innate left-handers. Because of plasticity the brain may compensate shifts of the writing hand.

In patients with early left-hemispheric lesions the consequences of such a lesion should depend on writing hand, innate handedness, and the size of the lesion, which is ascertainable to a certain degree. In left-handers with a left writing hand such consequences are not to be expected and undisturbed speech is right-hemispheric. The capacity of the left cerebral hemisphere to compensate the switching of the writing hand may be lower in SLHs with early left-hemispheric lesions, than in persons without such a lesion. Therefore, it can be expected that speech is represented in SLHs more in the right hemisphere despite right hand writing.

Unfortunately the authors did neither report the writing hand of the patients nor their age. As the data were collected between 1958 and 1976 it can be expected that all (or nearly all) persons that were classified as right-handers and also a significant amount (possibly 50% or more) of all left-handed participants (cf. Hugdahl et al., 1993; Tan, 1983) were writing with the right hand.

Under this assumption and based on the above considerations regarding left-hemispheric lesions and lateralization of speech, the above presented findings by Rasmussen and Milner (1977) can be expected: Irrespective of their writing hand more innate left-handers showed right-hemispheric speech in the case of left-hemispheric lesions compared to patients without a lesion. Such a result should be observable, despite the fact that innate left-handers might be classified as left- or right-handers. Innate right-handers should not bias the result. As right-handers do not use the left hand for writing, their speech cannot be shifted to the right hemisphere. Therefore, speech can be expected in the left hemisphere regardless of a left-hemispheric lesion or none. A lesion severe enough for total loss of speech would be a clear signal for a lateralization of speech in the injured hemisphere but this is not the case in this study. It is not reported that patients did not show any speech. Finally, the differences between patients with and without early left-hemispheric lesions regarding the lateralization of speech can be explained qualitatively. In concordance with and on the basis of the alternative model of handedness the differences might be induced by an interaction of two factors, right-hemispheric speech in left-handers and switched writing hand.

Some more recent studies controlled for the writing hand and made some discoveries, which are contrary to the previous theory on lateralization of speech and language. In reading (left- and right-handers) and writing (only right-handers) tasks with letters, pseudoletters, and a control stimulus Longcamp, Anton, Roth, and Velay (2003 [with right-handers], 2005 [with left-handers]) demonstrated a strong connection between handedness and brain activation. Reading letters, but not reading pseudoletters or reading the control stimulus, activated, besides other left-hemispheric areas, the left premotor area in right-handers (Longcamp et al., 2003). Writing letters (and pseudoletters) also activated the left premotor area in right-handers more strongly, than writing a control stimulus. In left-handers that were exclusively writing with the left hand some right-hemispheric areas were more activated during reading letters compared to reading pseudoletters (Longcamp et al., 2005). The right premotor cortex in left-handers was symmetrically located compared to the activated area in right-handers. Both studies reported that right-handers in reading and writing and left-handers in reading showed increased activation in an area that is part of the Broca area (Brodmann's area 44) during the experimental condition (reading letters) compared to the control condition (reading pseudoletters and/or the control stimulus). Activation in left-handers was also in the Brodmann area 44 but in the right brain hemisphere. Finally, both studies suggest for individuals without switched writing hand that left-handedness is associated in certain respects with a lateralization of speech in the right hemisphere, and that right-handedness is linked to left-hemispheric speech.

Nevertheless, it remains unclear, and this is one of the most relevant and unsolved problems in functional brain research, what the cause and what the consequence is. Is there a left- or right-hemispheric activation because the participants are right- or left-handers or because they practiced writing with the right or the left hand for about two decades (cf. Longcamp et al., 2003, 2005)?

A study by Siebner et al. (2002) may provide some answers to this question. They analyzed the problem of whether switching the writing hand, a procedure, which was common in Germany towards nearly all left-handers until some decades ago, produces long term consequences regarding the functional neuroanatomy of handwriting. Brain activation was observed while the participants repetitively wrote a stereotyped German word. The test procedure was administered to 11 switched left-handed adults and 11 age-matched right-handers. These 22 attendees were exclusively proficient in writing with the right hand and were so since early childhood. Additionally, a control group of six left-handers writing with the left hand participated. For innate right-handers, a left-hemispheric activation in some language related premotor and parietal areas was detectable while writing. Compared to that SLHs showed a more bilateral activation of the cortex. Siebner et al. offered two interpretations for these persisting differences in functional neuroanatomy in SLHs and right-handers (p. 2816). Either the right-hemispheric activation in SLHs may present the suppression of unwanted left hand movement, or it demonstrates persistent left-handedness despite writing with the right hand for decades. For the control group of nonswitched left-handed individuals with left handwriting, a strong right-hemispheric activation was found, while they were writing with the left hand.

The studies by Longcamp et al. (2003, 2005) and Siebner et al. (2002) provide some valuable results and may lead to a new approach in handedness research: First, the lateralization of language, at least in writing and reading, seems to be mirror reversed for left- and right-handers when they are writing with the dominant hand. Second, the results show a relationship between handedness and lateralization of language (or more specific: lateralization of speech). Third, brain imaging could get a diagnostic instrument to determine handedness because a strong lateralization of speech (and language) in one hemisphere may indicate that an individual is not switched (i.e., writing hand expresses innate handedness). Bilateral brain activation however indicates a switched writing hand.

Finally, permanent practicing of writing with the right hand leads to left-hemispheric lateralization of speech in SLHs, but the outcome of such training is limited despite the plasticity of the brain as the results by Siebner et al. (2002) and by Rasmussen and Milner (1977) imply. Some left-handedness or *right-brainedness* is remaining in SLHs and it should be the aim of future research to develop methods to determine whether a person is innate left- or right-handed irrespective of writing hand.

The proposed lateralization of speech and motor dominance in the same hemisphere is probably caused by a common evolutionary development of both features. Switching the writing hand may influence and impair this joint localization of both functions. The disturbance of the functional organization of speech and motor dominance might be a plausible explanation that switching the writing hand could lead to language impairments.

However, even the switching of hand preference and hand use of left-handed children who have not yet learned to write causes language disturbances. Sovák (1968, p. 244, p. 246) and Orton (1937, pp. 194-195) reported cases of stuttering of left-handed children who were forced to use the right hand. Stuttering vanished when the pressure ended. This disturbed speech production caused by a switching of hand use supports the ideas of (a) a combined lateralization of speech and motor dominance and (b) right-hemispheric speech in left-handers. Right hand use seems to be too demanding for the left hemisphere, which is not dominant for speech and motor functions.

The symptoms that lead to a concept of PLH should be apprehended in a new way according to the theory of innate handedness and related lateralization of speech. The clinical syndrome of PLH describes causality between an early left-sided brain injury and the occurrence of left-handedness (Satz, 1972, Satz et al., 1985). This approach discusses two independent characteristics (left-handedness and brain injury and its consequences) as connected with each other. The whole concept of PLH is based on two questionable assumptions and one inaccurate inference. First, it is assumed that left-handedness is qualitatively different from right-handedness and is evoked by different reasons than right-handedness. However, both types of handedness are caused by a random process and a distinction between pathological and nonpathological handedness does not make sense. Handedness is independent from other incidents like early brain injury. Second, it is assumed that speech is left-hemispheric in all or most humans. Therefore, lesions of the left hemisphere are perceived as cause of a right-sided speech representation, which is considered a part of the PLH syndrome. However, according to my theory right-hemispheric speech is normal in left-handers and found in healthy left-handers without any brain lesions (Longcamp et al., 2005; Siebner et al., 2002). Third, an early left brain injury may provoke some impairment like impaired visuospatial functions or hemihypoplasia of the right upper and/or lower extremity (Satz et al.). However, the existence of such a brain injury is misconceived as a reason for the more far-reaching inference that left brain injury does not only induce the described impairments, but also induces both left-handedness and a shift of speech representation to the right hemisphere.

A separate model of PLH is neither necessary nor does it improve the comprehension of handedness. The alternative model of innate handedness provides a sufficient reason for left-handedness in combination with right-hemispheric speech. The model explains as well the reported "relatively preserved verbal cognitive functions" (Satz et al., 1985, p. 33), which are lateralized in the undamaged right hemisphere. The other described symptoms of PLH especially those concerning the right limbs can be seen as the consequences of left-sided brain injuries. Altogether, I do not regard any handedness as pathological neither right-handedness nor any type of left-handedness. All kinds of handedness are innate and nonpathological. PLH does not exist.

### 3.1.6 Sidedness: An Extended Concept of Handedness

In the above part (3.1.5 *Human Handedness and Lateralization of Speech*) the model of innate handedness was broadened by the concept that handedness and lateralization of speech are connected. Additionally, I would like to discuss the term handedness in more depth. Handedness in a sense of a dominant or preferred hand is only one aspect of motor preference. Handedness (an alternative term could be sidedness) means that not only a hand is dominant but also a foot or a leg, and that the movements of the whole body are subject to a motor program, which is mirror reversed for left- and right-handers. Postural activities for stabilizing and moving the body (e.g., sitting down and standing up from the floor, jumping, sitting cross-legged, stepping into a sack, or climbing stairs for infants in their second year of life) are often asymmetric and can reflect different motor programs or different handedness/sidedness.

Even a relationship between handedness and visual or acoustic perception (either left or right dominant) may exist. A connection between handedness and eye dominance could cause a better coordination of the body (e.g., hand and eye coordination when catching a ball).

## 3.2 Switching Handedness, Different Degrees of Influence, and Consequences

Beside the innate component of human handedness a second element, the influencing and switching of handedness, can be ascertained. Three basic factors contribute to the handedness of an individual. First, an innate, mirror reversed and asymmetrical structure of the brain of left- and right-handers, second, plasticity of the brain and third, a social factor by means of influence, instruction, and example. The first one has already been discussed. The focus will be now on the aspects of instruction and learning ability. It is obvious that the plasticity of the brain is very extensive. Even recognized left-handers were forced to perform writing, the most complex manual activity of humans, with the right hand. And most of them were successful for decades.

To what extent individuals are influenced and switched in their handedness and how effective switching attempts are, depends on internal features, either individual or species related, and on external social or cultural factors. On the one hand, the intellectual capability of an individual, which is expressed (a) by a level of attention, (b) by the ability to understand instructions and to learn from observation and example, and (c) by the intention to comprehend and accept norms and to comply with, is crucial. On the other hand, motor ability and motor skill is relevant. The individual skill may differ because of different innate strength of handedness. The U-shaped distribution of handedness in some nonhuman primates, in mice, and particularly in the HI and LO strains of mice with different strength of handedness demonstrates such skill differences. Other factors may be age and sex. Adult nonhuman primates are stronger lateralized than immature individuals (Brooker et al., 1981; Hopkins, 1995b; Lehman, 1978; Ward et al., 1990; Westergaard & Suomi, 1996) and human males are more often left-handed than females (for details compare 2.1 *Previous Methods, Results, and Theories*). On species level the same characteristics are relevant for different degrees in switching and influencing handedness: Intellectual and motor skills of species.

Some of the external factors like a social norm, cultural pressure towards conformity, belief, exemplary function of parents and teachers, and more practically, the disposability of left-handed tools are probably human specific. It seems that only humans think about the concept of handedness and enforce their ideas regarding handedness towards other humans or animals.

### 3.2.1 Influencing Handedness of Animals

In several experiments nonhuman primates and other mammals were intentionally influenced in their hand or paw preference in order to study impact and effectiveness of external influence. These intentional influences will now be discussed. Influences that seem to be accidental are also of interest in this discussion. Two studies (Hopkins, 1995a, 2006) suggest such an unintentional influence on handedness. Although such an unintentional influence may exist, it is difficult to analyze it.

In a biased world mice mainly showed (86% and 90% in the first and second trial) a lateral preference consistent with the world bias (Collins, 1975, 1977). Female mice are more resistant to the environmental bias than male mice.[8] As the animals did not remain permanently in the biased environment but were only there for two trials with 50 paw reaches, the study cannot prove the permanence of the training. Collins (1991) demonstrated in an experiment with a combination of different world biases and mice with different degrees of lateralization (HI and LO lateralized strains of mice) a differing effectiveness of the world bias. Mice from the strain with low lateralization conformed to the world bias and HI line mice were resistant to the bias.

In an experiment with two mice as teachers and other mice as pupils Collins (1988) ascertained an influence on hand preference by social learning, which is a relatively weak measure of enforcement of a certain lateral behavior compared to an environmental world bias. In this experiment one teacher was trained to open a pendulum door to the left. The other teacher learned to open the door to the right. The trained mice ($N = 55$) were randomly assigned either to the experimental group or to the control group. The

[8] Under the assumption that 50% of the individuals of both sexes are left-handers, this appears to be reverse in humans. In our right-handed world, more left-handed males than left-handed females behave inconsistently to the world bias as males tend to be more left-handed than females (cf. 2.1 *Previous Methods, Results, and Theories*).

experimental group had the possibility to observe one of the teachers. The control group was placed behind a barrier and their view of the teacher was blocked. After observing (or without observing) the teacher, the mice from the experimental group were faster in the first trial to open the door than the mice from the control group. In further trials the difference diminished as the control group gained experience in how to open the door. Male mice from the experimental group opened the pendulum door in the same direction as they were shown by the teacher. As they had to perform 11 trials, a certain learning effect can be assumed. The control group and the females in the experimental group did not adopt the instructor's laterality when opening the door. Finally, Collins (p. 224) speculates that social learning of humans may also cause local traditions of lateralization (as we can observe it in Western and non-Western societies) and a cultural diffusion of behavioral asymmetries even when coercion is absent.

Peterson (1951) analyzed the change of handedness in rats by means of forced practice. After paw preference was determined in a first stage of the experiment, food was provided in a biased food dish in such a manner that animals could only reach with the nonpreferred paw. Additionally, attempts to get food with the preferred paw were stopped. This training was carried out for 1 to 20 days with 50 reaches per day. Depending on the duration of the training the rats changed hand preference. After 2 or 4 days of training preference was shifted in 50%. Eight to 20 days of training lead to a transfer in more than 70% of the animals.

In a second experiment the initially determined preferred forepaw of an animal was bound with adhesive tape against the body. For the experimental group, the training with the nonpreferred paw was similar to that in the first experiment. Food was provided in a biased food dish and animals were forced to use the nonpreferred paw. In the control group the preferred paw was also bound, but these animals were not trained and could reach for food in an unbiased set-up. After the training period, the paws of both groups were unbound and food was presented in a center-dish situation. Although arms were stiff for a day or two Peterson (1951) reported that the control group was uninfluenced from having arms bound and used the unbound preferred paw nearly exclusively. In the experimental group more than 60% of the animals changed their paw preference in 75% to 100% of paw reaches. There was a trend towards more frequent use of the nonpreferred paw as the training period grew longer (5 to 29 days for different animals).

The results of both experiments support that forced training with the nonpreferred hand is the reason for the preference shift and not the binding of the paw in the second experiment. It is also clear that training is not the only factor that determines handedness. The initial individual degree of handedness is another relevant factor. In both experiments the training of some animals was ineffective and they often returned to the preferred paw even after the maximum length or at least after a long period of training.

Experiments with nonhuman primates also clarify that hand preference can be changed by training. In three test sequences Kempf (1917) determined the preferred hand of 6 rhesus macaques for grasping food. Three of them showed clear handedness to either direction. The other 3 animals had in the last test sequence a tendency towards one hand, which was regarded as preference in the following. Then the monkeys were forced by a tough incentive system to use the nonpreferred hand for grasping food. Nutrition was offered, but not released and withdrawn when the animals tried to reach with the preferred hand. Food was offered again a few seconds later. Each monkey grasped repeatedly but unrewarded with the familiar hand. After up to 77 unsuccessful attempts on the first day, all monkeys managed to use the demanded nonpreferred hand and the procedure was continued until the error rate of grasps with the preferred hand was low. A few months after the training period, the animals were retested and only 1 animal used exclusively the previously preferred hand for grasping food. The other 5 maintained the instructed habit to reach with the initially nonpreferred hand.

Lehman (1980) carried out a similar experiment with 46 stumpnail monkeys. In the first trial of the first session, food was offered and always withdrawn irrespective which hand the monkey used. Food was then offered again. It was withdrawn as long as the animals grasped with the same hand as in the first trial. A grasp with the other hand was rewarded with the offered food. All following reaches in the first session, and all reaches in the next five sessions up to 100 reaches per session were rewarded regardless which hand was used. The experiment lasted 3 days with two sessions per day. The aim of the experiment was to find out which animals easily switch their hand to get the first reward and to determine the preferred hand in the following 600 reaches. Those monkeys, which demonstrated a more consistent preference and sooner came back to the hand used in the first trial for the rewarded reaches, were also the animals with a stronger preference as they used the hand of the first trial for 85% to 100% of all rewarded reaches. Overall these individuals remained persistent in their hand preference, despite the initial training. The incentive to use the nonpreferred hand was much weaker than in Kempf's (1917) experiment as the training/enforcement period was only short and at the beginning of the experiment. In Lehman's study the monkeys had to reach at least once with the hand, which was not used in the first trial. After this they had a free choice. Furthermore, the experimental procedure did not rule out the possible but unlikely case that monkeys may have reached with the nonpreferred hand in the first trial. For such animals successive reaches with the other hand were not a hardship.[9] In contrast, Kempf's study shows that the hand preference of animals was first determined and then they were coerced to always reach with the nonpreferred paw.

McGonigle and Flook (1978) determined in the first stage of an experiment the preferred hand of 6 squirrel monkeys. The animals had to push a colored tin to get food and had a free choice of which hand they used. After four sessions (each session with 40 trials) 5 of 6 monkeys showed a preference for one hand. In a second stage the animals were trained to push a new tin with a different color with the nonpreferred hand. They were rewarded only when they did so. In the first and second session error rates were a little over 50%, but in the forth and fifth session more than 90% of acts were with the rewarded hand. In the third stage the subjects were retested. Although the monkeys could obtain the food in this stage regardless of the acting hand, they continued with the nonpreferred hand.

In a second experiment the monkeys learned to reach with the preferred hand for the first color and with the other hand for the second color and were able to differentiate between the colors in the training period. But after some weeks without training the subjects lost the ability to distinguish between the two different cues.

The studies with mice, rats, and monkeys on intentional influence on handedness demonstrate that coerced switching of hand preference with different measures (environmental biases, withdrawal of food, and rewards for demanded behavior) is effective and permanent. Two studies by Hopkins (1995a, 2006) suggest that unintentional influences may cause a shift to right-handedness in chimpanzees. A hand preference test with a reaching task showed interactions between the kind of rearing (mother reared or nursery reared) and both direction and strength of hand preference in juvenile chimpanzees (Hopkins, 1995a). Mother reared animals were more strongly lateralized, and did not have a predominant handedness on population level (9 left-handed, 8 right-handed, and 1 weakly lateralized). Nursery reared apes were less lateralized and demonstrated

[9] Signore, Nosten-Bertrand, et al. (1991) reported from a food reaching task with mice that 81% of the females and 75% of the males were acting with the preferred paw in the 1st of 50 paw reaches. However, it can be expected that some animals in Lehman's (1980) study started with the nonpreferred hand and were therefore privileged as they were forced in the second grasp to change from the nonpreferred to the preferred hand and not vice versa.

with 20 right-handers, 9 left-handers, and 4 weakly lateralized subjects predominant right-handedness on population level. According to this study (Hopkins, 1995a) and the previously cited meta-analysis on handedness in great apes (Hopkins, 2006) a trend towards right-handedness exists in animals, which lived in captivity and were raised by humans. Wild apes or at least mother-reared apes do not show such a trend towards right-handedness. Finally, it remains an unsolved mystery as to what causes such a confusing and unusual result as Hopkins (2006) emphasized that "social learning is not the most likely explanation for the development and heritability of hand use in chimpanzees, although as stated previously, this explanation cannot be entirely ruled out" (p. 551).

### 3.2.2 Influencing Human Handedness and Consequences for the Distribution

The observable strong deviation of the distribution of hand preference from the proposed 50:50 ratio of left- and right-handers in humans implies that handedness is influenced and switched in many individuals.[10] Intentional influence in psychological experiments by means of coercion like in animal research is almost not possible in humans for ethical reasons. Convincing results have to be found by observation and by comparison. Interesting findings can be expected in research with children for the following reasons: (a) Because of a shorter lifetime they are less influenced, (b) due to a lower level of attention they are probably less able to be influenced, and (c) their ability to comprehend instructions is not fully developed.

Another advantage in research with children is that they cannot fill out questionnaires. Research with children, which relies on observations, seems to be a better method than administering questionnaires. Activities, which neither are under social control nor are related to activities under social control, should be of special interest. Some studies demonstrate that a naturalistic test approach with young participants causes results

[10] An extensive overview of environmental and cultural influences can be found in Harris (1992) and in great detail in Harris (1990). While studying the time period between the ancient world and the beginning of the 20th century Harris (1990) outlined several aspects of influencing handedness: (a) The existence of requirements how activities like writing, eating, and gestures had to be performed; (b) the restrictions on left hand use; (c) the incidence of left-handedness; (d) the attitudes towards left-handedness and the change of attitudes; and (e) the development of speech in SLHs. Regarding more recent times (second half of 20th century) his focus was mainly on (a) differences in prevalence of left-handedness in liberal and conservative countries and societies, (b) sex differences, (c) social transmission of attitudes and behavior, and (d) "Psychological Effects of Forcible Shifting of Left-Handedness" (Harris, 1990, p. 226). The following considerations regarding influence on human handedness and the next subsection on differences between left-handers, right-handers, and SLHs will deal with some of these topics.

regarding the distribution, which are deviating from the results of the questionnaire approach. The distribution comes close to a ratio of 50:50 of left- and right-handers.

From societies and groups with differing attitudes towards left-handedness and differing degrees of social pressure insights can be achieved about influencing and switching handedness. This approach comprises of families with left-handed parents and their children, societies with a past or current change of social pressure on left-handers, or the comparison of societies with differing attitudes towards left-handedness.

Due to extensive social influence only few studies report a ratio of 50:50 of left- and right-handers. Among them are two studies on hand preference in infants and children (age between 6 months and 6 years). The results by Lederer (1939) and Bethe (1925) are remarkable because younger children demonstrated either a strong or weak hand preference for one hand and showed on population level a 50:50 ratio of left- and right-handers. This U-shaped distribution was not true for older children. A trend towards a preponderance of right-handedness could be found for this group. Three other studies demonstrated with pooled data a ratio of 50:50 of left and right hand use in manual activities.

Lederer (1939) examined infant handedness and the formation and development of handedness from the ages of 6 to 30 months. The children ($N = 164$) had to perform a 22 items test with age-based activities like reaching up for a toy or ringing a bell. As 134 participants were retested after a few days consistency of the test could be demonstrated. The selected items had to satisfy three criteria: Activities were chosen when they were (a) more unimanual, (b) more consistent (i.e., upon repetition the activity is performed with the same hand), and (c) more preferential (i.e., an activity is more often performed with the preferred hand) than others. Two strengths of this item selection policy are that there is no or little social control on most of the items, and that only two items examine the use of tools (eating with a spoon and drawing with a pencil). Two weaknesses are that most activities are performed with an object (bell, toy, cloth, and food), and that only unimanual activities were included in the test. Lederer attempted to validate her test as she observed a few infants ($N = 7$) for a longer time to learn more about the hand preference of these infants and compared these results with the test results. She declared that even in the preliminary stage the test is a good indicator of the infants' hand preference. For the 134 retested children Lederer analyzed the status of handedness and ascertained the distribution of left- and right-handedness in diverse age groups.

For another group of 29 infants Lederer (1939) recorded longitudinal data and tested them two to five times with time gaps from 2 to 12 months. The test results for this group clarified how handedness changes and develops.

Based on data from both experiments Lederer (1939, p. 71) concluded for the development and distribution of handedness the following: First, in the second half of the first year of life there are about equal numbers of left-handed and right-handed infants, with only a small fraction of unclassified children (less than 20%). Second, nearly 80% of the children in the age group from 12 to 23 months (second year of life) are right-handed. Third, an effect of sex on the distribution of hand preference cannot be found. Fourth, the longitudinal comparison reveals that handedness changes more often in the first year of life than in the second year and that handedness changes more often from left to right than vice versa. Fifth, the strength of hand preference is for all age levels approximately similar.

In a discussion on the causality of preferential hand use Lederer (1939, pp. 75-77) annotated that the above cited results for older children were more and more driven by items, which she calls social items. She regarded the applied activities like eating, drinking, waving, drawing, and presenting an object as instructed and conditioned for right hand performance. Finally, it seems that she tended nevertheless to take the position that humans are by nature predominantly right-handed and that the development of individual handedness with increasing age is the reason why most people are right-handed.

A study published in German by Bethe (1925) also demonstrates the result that the distribution of left- and right-handedness is dissimilar in infants of different age groups. Bethe determined with various items like eating with a spoon, picking up objects, and pointing on objects the hand preference of children. Additionally, he observed the infants when they were left to their own resources and were not aware of being monitored. He ascertained that the distribution of hand preference in infants from 2 to 4 years ($n = 42$) was nearly symmetric. A very strong preference for the right or rather left hand showed in each case 16.7% of the children. A preference for either hand demonstrated 23.8% (left hand preference) and 21.4% (right hand preference) and no preference was observable in 21.4% of infants. For children at the age of 4 to 6 years ($n = 53$) the figures were 17.0% for strong left hand preference, 1.9% for left hand preference, 5.7% for no preference, 24.5% for right hand preference, and 51.0% for strong right hand preference. As Bethe observed two age groups but did not gather longitudinal data, he could only present that handedness seems to have different distributions in different age groups but he could not report any development and change of hand preference.

Carlson and Harris (1985) tested 32 infants in seven sessions, beginning at an age of 24 weeks up to an age of 39 weeks. They tested them every 3 weeks and once again at an age of 52 weeks. The participants were 8 girls and 8 boys with right-handed parents (familial right-handed, FRH). Another 8 girls and 8 boys had at least one left-handed parent (familial left-handed, FLH). In each session the infants had to perform 54 reaching trials with objects of differing size. The distance and the lateral position (midline, left, and right) were varied. The FRH girls were the only group that consistently used the right hand for a majority of reaches. At an age of 52 weeks FLH boys, FLH girls, and FRH boys had more reaches with the left hand. At this age each of the four groups had a ratio between 60:30 and 30:60 for left and right hand reaches and about 10% bimanual trials. Altogether, the data do not indicate a 10:90 preference for the right hand (not even for FRH girls and FRH boys) but an approximately equal frequent use of both hands.

Although the authors comprehend their findings in a different way, the data published by Rönnqvist and Domellöf (2006, p. 450) provide similar results. At age of 6 months children did not demonstrate a clear preference for unimanual left, unimanual right, or bimanual hand use when grasping objects. At age of 9 months reaches were almost completely unimanual but without a preponderance of left or right hand preference. But at the age of 12 months a right hand preference was established and the right hand was used for more than 60% of reaches whereas the left hand was used for about 33% of reaches.

In the above (cf. 2.2.7 *Alternative Methodology of Testing*) in detail quoted study Marchant et al. (1995) provided data, which were pooled for all participants and all manual activities. On the basis of these data they demonstrated that adults used the right hand (53% to 55% of all acts) only slightly more often for nontool activities than the left hand (45% to 47% of all acts).

The above presented studies suggest that some instances like a naturalistic approach of testing, young participants, and low pressure towards right-handedness facilitate that the real distribution of handedness, instead of the usual majority of right-handers, can be determined with such tests. Another reason for the increased frequency of left-handedness could be what I call the *phenomenon of the precise view.* When parents or researchers make some effort to diagnose innate handedness they get qualitatively better results and find a higher prevalence of left-handedness.

This is particularly true for left-handed parents. Due to their own handedness they may be more aware that offspring could be left-handed, either for genetic or other reasons.

As they observe the development of the hand preference more attentively they notice left-handedness more often in their daughters and sons. Otherwise, on the basis of popular belief fewer left-handers are expected in offspring of right-handed parents. The recording of handedness of this offspring is probably incorrect and fewer left-handers are found, than in offspring of left-handers. Therefore, an apparent heredity of left-handedness seems to exist.

Previous research explained the fact of increased prevalence of left-handedness, which results in a 50:50 ratio of left- and right-handed children in some studies with offspring of two left-handed parents, by means of a genetic theory of familial left-handedness (cf. Annett, 1985; McManus, 1985b). But the *precise view* could be the actual reason. Instead of a concept of genetic heredity of handedness I propose a model of sociocultural heredity where left-handedness runs in families. As left-handed offspring should occur with the same frequency in all families, the crucial point is not whether left-handedness exists but whether left-handedness of an infant is noticed. This depends possibly (a) on sociocultural attitudes; (b) on the familial attitudes towards handedness and the attention of parents or teachers; and (c) on the strength of handedness, as strong left-handedness is easier to recognize than weak lateralization. The first of the three factors is the most general one and is subject to long-term changes. The familial factor is hereditary as well as changeable on a short-term perspective from one generation to the next. Only the third factor is completely genetic and not subject to any change in attitude or behavior. Although data about the factors, their changes, and their effects are not available, some data on familial handedness indicate a cultural heredity instead of a genetic heredity. On the one hand, studies show a general increased prevalence of left-handedness in the course of the 20th century because of a more permissive attitude towards it, and on the other hand, a higher incidence of left-handedness or left hand preference (often the writing hand) exists in families with left-handed parents. Between 20% and slightly more than 50% left-handed offspring were reported by Annett (1974, 1983), Chamberlain (1928), Dahmen and Fagard (2005), McGee and Cozad (1980), and McManus and Bryden (1992). The latter authors presented aggregated data-sets from several studies. The rate of left-handedness in offspring is between two and six times higher when parents are left-handed (mother, father, or both) than in families with two right-handed parents. Even the differences among left-handed families seem to reflect the familial and social reality in rearing children. Two left-handed parents induce the highest frequency of left-handedness in offspring and the maternal effect is stronger than the paternal effect in parents with discordant handedness. Finally, the theory of familial left-handedness should be understood more as a self-fulfilling prophecy, which is based on insufficient observations and biased testing and measuring.

Furthermore, the social pressure towards right-handedness may provoke a seeming relationship between familial left-handedness and individual strength of handedness. As right-handedness relies on a social norm, only these 5% to 15% of left-handers who demonstrate a strong lateralization are possibly perceived as such. If the strength of handedness in humans is innate as I propose by means of the alternative model of handedness and as Collins (1985) showed for mice, it can be expected that the filial generation of recognized (strongly lateralized) left-handers is also strongly lateralized. Nevertheless, the direction of handedness is random in the filial generation. Although Gangestad and Yeo (1994) interpreted their data from a study on familial handedness and hand skill in a quite different way, they presented that the parents of extreme left-handers and extreme right-handers are more often left-handed than parents of less lateralized participants. Additionally, the analysis of the distribution of relative hand skill showed that the *mean* relative hand performance of offspring with at least one left-handed parent and of offspring with two right-handed parents did not differ (i.e., left-handers do not have more left-handed children than right-handers). However, the *variance* of hand skills was higher in offspring with at least one left-handed parent (i.e., left-handers may be stronger lateralized and may therefore have stronger lateralized offspring; either left- or right-handed). Altogether, the authors did not detect a relationship between left-handedness and strength of handedness but demonstrated that left-handers are only perceived as such when they are strongly lateralized. According to my model, the weakly lateralized left-handers are not detected as left-handers. Finally, they get switched regarding writing hand and hand preference.

A switching of the writing hand in left-handers (already discussed in 2.2 *Discussion of Methods and Results of Testing*) is found in Western (Beukelaar & Kroonenberg, 1986; Hugdahl et al., 1993; Porac et al., 1986; Searleman & Porac, 2001, 2003) and Eastern cultures (Ida & Mandal, 2003; Shimizu & Endo, 1983; Teng et al., 1976, 1979). This illustrates clearly the social influence on hand preference, which is the most complex manual activity for humans. The switching of the writing hand in combination with right shifts in other activities (Searleman & Porac, 2001) suggests that shifts in hand use of left-handers are not limited to only a few activities under social control like eating and writing but may influence general hand preference. Hence, it is impossible to estimate the extent of switching handedness as any previous test for hand preference may be biased.

Gaillard and Satz (1989) demonstrated for 124 children who were tested two times at an age of 5 and 9 years a trend of decreasing incidence of left-handedness (cf. Lederer, 1939; Bethe, 1925). A predominance of right-handedness on population level existed when children got older. Such an increased right-handedness in older children may be either explained as a consequence of a maturation process or by social influence.

An age effect, which is probably a consequence of influence and a social norm, can often be found and not just in children. Several studies in Western societies (US, UK, Australia, and New Zealand) showed that a relationship between age or year of birth and the percentage of left-handedness or left hand writing in an age cohort exists (Brackenridge, 1981; Ellis et al., 1988; Fleminger et al., 1977; Gilbert & Wysocki, 1992; Hugdahl et al., 1993). For the comparatively liberal Arabian country Tunisia Dahmen and Fagard (2005) also referred to a connection between age and the frequency of left-handedness.

The age effect exists even in families: For three generations an increase in left-handedness is reported from 6.2% (grandparents) up to 17.5% (grandchildren born in 1971) for a UK sample (Smart et al., 1980) and from 1.2% (grandparents born 1895 - 1925) up to 8.7% (grandchildren born 1955 - 1985) for a Norwegian sample (Tambs et al., 1987). The effect of increasing left-handedness in the filial generation is also observable for two generations (Ashton, 1982; Dahmen & Fagard, 2005; Spiegler & Yeni-Komshian, 1983; Tan, 1983).

In countries like China, India, and Japan the frequency of left hand writing or left hand preference is low compared to Western countries (Ida & Mandal, 2003; Shimizu & Endo, 1983; M. Singh, Manjary, & Dellatolas, 2001; Teng et al., 1976, 1979). Within the context of the alternative model this can only be explained by social influence. In countries with a harsh attitude towards left-handedness the incidence of left hand writing and eating is exceptionally low, but also other activities are more often performed with the right hand (Shimizu & Endo; M. Singh et al.; Teng et al., 1976, 1979). Under the assumption that handedness is genetically inherited as it was proposed by McManus (1985b) another explanation for different ratios of left-handedness can be considered. Bryden, Roy, McManus, and Bulman-Fleming (1997) suggested that either a higher social pressure or the lower frequency of the C gene, which causes left-handedness with a certain probability, in the gene pool may be the reason for a lower incidence of left-handedness in one society compared to others. A model with two factors, differing social pressure and differing frequency of the C gene, was verified with data on familial handedness in

Canada and India. They concluded that a difference in gene frequency is more likely to be the cause of decreased left-handedness in India rather than a social norm and influence.

Ashton (1982) provided data from Hawaii on social influence and increased left-handedness in the filial generation, which suggest a contrary argumentation. He reported that the proportion of LHWs increased from the parental to the filial generation in the Hawaiian population of European origin from 7.1% (both males and females) to 11.9% for males and 9.1% for females. The figures for the Hawaiians of Japanese ancestry were much lower for the parental generation (0.8% for males and 1.6% for females) but somewhat higher in the filial generation (13.2% for males and 10.0% for females) compared to the population of European origin. Whereas the parental generations of European and Japanese origin were probably socialized in different social environments the filial generation grew up in the same society. Therefore, the data suggest understanding the different frequency of left-handedness in the parental generations as predominantly caused by environment and not by genes. The similar frequency, which is far from 50% of left-handers, in both filial generations can be understood as an expression of the common sociocultural context, which leads to approximately 10%, 12%, or 14% of left-handers.

Handedness in twins and especially in monozygotic twins is an interesting case as beside the innate handedness and the influential factors there is a further effect. Twins are two identical or fraternal siblings of the same age. In twins it is much easier for parents to perceive discordant handedness in their offspring than in any other birth order. Hence, left-handedness can be more often found in monozygotic and dizygotic twin pairs than in the general population of the same age (Orlebeke et al., 1996; Rife, 1940; P. T. Wilson & Jones, 1932). Other familial effects were as well reported by Orlebeke et al.: (a) Male offspring are more left-handed than female offspring, (b) left-handed parents have more frequently left-handed children, and (c) a stronger maternal effect exists in parents of different handedness.

The highest incidence of left-handedness in healthy population is reported from Tunisia for a small group of offspring (n = 22) of two left-handed parents (Dahmen & Fagard, 2005). The frequency was slightly higher than 50% (12 of 22). Taking the research results from decades and the popular belief into consideration, even in representative samples unexpected high frequencies of left-handedness are observable: A remarkable difference in the prevalence of left-handedness between the capital Tunis and smaller cities or towns was reported by Dahmen and Fagard. Between 22.7% and 13.6% of the participants in Tunis, subdivided into three groups of age and of both sexes, have a left writing hand.

In other areas of Tunisia between 14.4% and 2.6% of the population use the left hand for writing. Smart et al. (1980) gathered data from 6 year old children ($N$ = 1,094), which were born in the same hospital in 1971, and determined 17.5% left-handers (boys 19.9%, girls 13.3%). Provins, Dalziel, and Higginbottom (1987) observed the manual behavior of 22 children in a nursery school entirely by video recording over 11 days. The analysis of the data showed that 23% of the children used the right hand less often for manual activities. Considering the duration of hand activities, 64% of the children had a right-hand dominance and 36% a left-hand dominance.

For a population of 180 Kwakiutl an American Indian nation in Canada including children, adolescents, and adults, Marrion (1986) reported 77% right-handed, 17% left-handed, and another 6% mixed-handed individuals. In a Caucasian sample, matched for age, sex, and geographic location, 7% in all age groups were left-handed and almost none were mixed-handed. In contrast to most studies the ratio of RHWs was not in adults but in 10 - 12 year old children at the highest level in the Kwakiutl nation. Adult Kwakiutl changed either their writing habits after they finished school or the attitude towards left-handedness was more liberal when they went to school. Furthermore, the Kwakiutl are an exception in handedness research not only for the small number of right-handers but also for another cultural characteristic. Marrion and Rosenblood (1986) found in Kwakiutl totem poles and house poles that depictions of human hand use were 24% left-handed, 20% right-handed, and 56% mixed-handed. Marrion and Rosenblood emphasized that "these findings are in marked contrast to other research findings on artforms, which show about 90% right-handedness" (p. 755). Nevertheless, it remains open whether an artist who illustrates human handedness mainly portrays real hand use or rather expresses sociocultural attitudes and beliefs of how hand preference should be. In the face of a slight preponderance of left-handedness compared to right-handedness in Kwakiutl totem-pole art and a majority of right-handers in current population, despite high and with age fluctuating frequencies of both left-handedness and mixed handedness, the authors suggested that a sociocultural and environmental influence on handedness (e.g., English graphology, tool use, and greater requirement for writing) favors right-handedness and that the real frequency of left-handers could even be higher.

Beside the discussed internal features, either individual or species related, the incidence of left-handedness in healthy individuals depends on several external factors, which are effective on different levels. The attitudes of the society induce a differing prevalence of left-handedness depending on country, ethnic origin, and year of birth or age. Family studies on handedness suggest the existence of a familial effect. The increase of left-handedness from generation to generation clarifies the relevance of familial attitudes and parental attention. On a society level as well as on a family level, education is probably an important factor for the incidence of left-handedness and the behavior and attitude towards left-handedness.

### 3.2.3 Prevalence of Left-Handedness in Clinical Patients

An increased frequency of left-handedness in several groups with mental handicaps compared to normal population has been reported for more than 80 years (Gordon, 1921; M. O. Wilson & Dolan, 1931). The increased frequency in such groups indicates also that handedness as it is currently perceived should be apprehended as partly innate and partly influenced. Attempts to switch hand preference in individuals with mental handicaps, which are for example expressed by (a) a reduced level of attention, (b) a limited ability to understand instructions and to learn from observation, and (c) motor deficits, may be more often unsuccessful than in normal unimpaired control groups. The lower capability of an individual to conform to shifting attempts induces a rate of left-handedness among clinical patients above the widely accepted frequency of 10% or 12%. Bethe (1933, pp. 781-782) referred decades ago that a more frequent switching of nonhandicapped left-handers compared to mentally handicapped left-handers is the cause of an increased incidence of left-handedness among clinical patients.

A fundamental assumption for this consideration is that handedness and impairment of cerebral functions must be independent from each other. According to the alternative model of handedness this assumption should not be problematic.

Especially in the cases of two genetic syndromes, Trisomy 21 and Williams-Beuren syndrome (WBS), there seems to be no evidence that handedness and cerebral asymmetry might be directly influenced or changed by the genetic syndrome, when handedness is genetic in a manner as Annett (1985) or McManus (1985b) proposed. Also autism, schizophrenia, and other cases of functional cerebral impairments with partly unknown etiology, do not seem to be caused by a lesion or a dysfunction of one brain hemisphere. All these syndromes are more or less caused by a general deviation of brain functions (possibly of both hemispheres) from normal state. Thus, these syndromes should be distinguished from the syndrome of PLH, which describes an early left-sided brain injury as an apparent cause of left-handedness.

Recent studies on handedness of patients with WBS, a genetic syndrome resulting from a hemizygous deletion of genes on chromosome 7, showed a high prevalence of left-handedness. By using a 10 item hand performance test Van Strien, Lagers-van Haselen, van Hagen, de Coo, Frens, and van der Geest (2005) found in a Dutch sample of 25 female and 25 male patients 26% left-handers compared to expected 11.6% in general Dutch population of the same age.

For 34 patients with WBS from different countries Carlier et al. (2006) reported slightly increased left-handedness (12%) but strongly increased mixed handedness (50%), when three categories of handedness were determined by using a performance test with 11 items (excluding matches) of Annett's (1970) questionnaire. By using an adapted card reaching test (Bishop et al., 1996), which may be of higher ecological validity for mentally disabled than a test with scissors and rackets, 29% left-handers were determined in an analysis with two categories of handedness. A three category analysis (right-, mixed-, and left-handed) comprised 38% mixed-handers, 21% left-handers, and 41% right-handers. For patients with Trisomy 21 ($N = 45$) Carlier et al. also ascertained increased left-handedness by applying the performance test with 11 items and the card reaching test. In an analysis with two categories of handedness about 30% left-handers were determined in both tests. A follow-up study (Gérard-Desplanches et al., 2006), which included the participants from the previous study (Carlier et al.) and additionally 17 cases with Trisomy 21 and 5 cases with WBS, confirmed the result that both groups of patients are less right-handed and more left-handed or mixed-handed than a group of typically developing persons. Gérard-Desplanches et al. also found that the preference for the left foot, left eye, and left ear was stronger in both patient groups than in the typically developing group.

In a review article on atypical laterality and retardation, Pipe (1988) reported an increased frequency of left-handedness (10% to 29%) and mixed handedness (6% to 43%) in patients with Trisomy 21 on the basis of five older studies. The summarized frequencies of left-handedness and mixed handedness ranged from 19% to 53%. For 18 studies with mentally disabled patients of unspecified etiology the rate of left-handedness was between 2% and 31% with a median of 16% and an average of 16.5%. The frequencies of mixed handedness in 11 studies were between 5% and 46%. The combined incidence of left-handedness and mixed handedness varied from 7% to 60% with a median of 25% and an average of 27%. One reason for the fluctuating frequencies of left- and mixed-handers is probably a differing classification of left-handedness, right-handedness, and mixed handedness. For autistic patients the frequency of left-handedness and mixed handedness is also significantly higher than in the normal population (Bonvillian, Gershoff, Seal, & Richards, 2001; Cornish & McManus, 1996; McManus, Murray, Doyle, & Baron-Cohen, 1992; Soper, Satz, Orsini, Henry, Zvi, & Schulman, 1986).

Although syndromes like WBS or Trisomy 21 are not related to distinct lesions or impairments of one brain hemisphere the increased incidence of left-handedness in mentally disabled patients is misconceived. Left-handedness is seen as pathological in a sense that natural right-handers switch to a consistent left hand preference due to lesions of the left hemisphere. As neither left-handedness nor right-handedness in mentally handicapped persons is related with a specific functional cerebral impairment, I suggest discussing left-handedness in the group of mentally disabled in the context of the alternative model of handedness. Handedness and individual strength of lateralization are innate and influenced by external sociocultural factors. The previous theory failed to notice that the aptitude of clinical patients to accept the social norm of right-handedness and to perform activities in this way is limited. Furthermore, it seems possible that the social pressure towards right-handedness is reduced in mentally disabled persons compared to the normal population. Increased left-handedness in clinical patients, which goes up to 50% but does not exceed 50% significantly, may indicate the actual 50:50 ratio of left- and right-handers.

### 3.2.4 Psychological Consequences of Switching Left-Handers

The switching of hand preference in left-handers may cause a variety of psychological consequences and problems. As writing is the most demanding motor activity of humans, the switching of the writing hand may cause more frequent and more severe consequences than a shift of hand use in other socially controlled activities, like eating with cutlery or cutting with scissors.

If the brain of a left- and right-hander is mirror reversed, as proposed, a shift of the writing hand of a left-hander implies that the nondominant left brain hemisphere, which is not responsible for speech and language production, is enforced to produce written words. An overexertion of the left hemisphere and of the brain in general can be expected. It has already been shown by Siebner et al. (2002) that a switching of the writing hand causes abnormal brain activity in the left hemisphere.

Even other manual activities with the nondominant hand (except for writing) may cause disturbances. Sattler (2000, pp. 11-16, p. 73, pp. 79-80) reported cases of a surgeon, a cashier, and a dental technician. They acquired severe psychological problems probably evoked by frequent fine motor activities with the nondominant hand, which were related to their profession.

Additionally, the psychological problems and consequences of a switched writing hand for behavior, intellectual capability, and personality are an important topic of research. Regrettably I could hardly find any systematic study on these consequences in English.

Orton (1937) reported writing disabilities (pp. 99-103) and stuttering (pp. 194-195) in left-handed children who were switched in hand preference. A retraining of the left hand led to the disappearance of the writing problems or the stuttering. Perelle and Ehrman (1994) found that learning deficits of "more than few students" (p. 223) were caused by a switched writing hand. A change to the left hand for writing eliminated most or all of the impairments in several cases. Whipple (1911) reported a case of a left-handed third grader who was coerced to use his right hand for several activities and subsequently "a speech defect nearly equivalent to stammering" (p. 575) evolved. A systematic study on stuttering in SLHs and nonswitched left-handers strongly indicates a relationship between stuttering and switched writing hand (Ballard, 1911-12). This study will be discussed in detail in the next subsection because the study also contains a comparison of two groups of left-handers (SLHs and LHWs).

Two books in German by Austrian and German authors (Rett et al., 1973; Sattler, 2000) and a book translated from Czech into German (Sovák, 1968) deal with the consequences of switched left-handedness, and provide results from several studies, from further research, and from counseling on this topic. Sovák (pp. 217-236) reported for 150 students (134 SLHs and 16 nonswitched left-handers) from preschool level to 8th grade (a) the process and the degree of switching, (b) the incidence of disorders in switched students, and (c) an improvement of disorders in students retrained for left hand writing. Some of the more frequent disorders are motor restlessness, behavioral changes, weak spelling, stuttering, failure in school, dyslexia, and dysgraphia. Rett et al. and Sattler reported some consequences of switching hand preference particularly of switched writing hand. Rett et al. (pp. 75-78) referred to vegetative symptoms (e.g., headache, sleeplessness, and fluttering eyelid) and behavioral symptoms like restlessness, poor concentration, aggression, depression, and stuttering. Rett et al. emphasized that the distinctness of behavioral disorders depends on the degree of handedness, harshness of the switching process, family situation, intelligence, character, and age of the switched child (p. 78). Sattler (pp. 49-50) differentiated between primary (e.g., memory disturbance, dyslexia, fine motor problems, stuttering, and stammering) and secondary consequences (e.g., feeling of inferiority, lack of assurance, seclusion, and defiance). Disorders that are related to writing and speech are particularly discussed. Sovák (p. 167, pp. 202-205) and Rett et al. (pp. 92-94, 95-102, 138-139, 174-176) reported a frequent and relevant causality between switched handedness and writing problems, stuttering, dyslexia, behavioral disorders, and impaired cognitive abilities. All authors (Rett et al.; Sattler; Sovák) stressed that switched left-handedness is a reason for the above variety of disorders and that such disorders arise more often in SLHs. Nevertheless, other causes may exist for these disorders apart from switched handedness.

## 3.3 Differences in Left-Handers, Switched Left-Handers, and Right-Handers

In this subsection, the consequences of an interaction of the two elements, which contribute to the formation and phenotypical appearance of human handedness, will be discussed. These elements are innate handedness, and influencing and switching of handedness. The research on switched left-handedness suggests that switching causes some psychological and behavioral differences between switched individuals (mostly former left-handers) and persons with nonswitched handedness (cf. Rett et al., 1973; Sattler, 2000; Sovák, 1968). Therefore, it is necessary to distinguish four combinations of innate and influenced handedness. Left- and right-handedness are the two kinds of handedness with a nonswitched dominant hand. The preferred hand is in accordance with the innate lateralization of motor dominance and speech. In addition, two other combinations of hand preference and functional cerebral asymmetry exist. Shifts of hand preference induce either switched left-handedness or switched right-handedness, but in a right-handed world the latter is an almost theoretical case.[11] Among other changes of hand preference the switching of the writing hand is probably the most important reason for psychological disturbances (Rett et al.; Sattler; Sovák). Therefore, the preferred hand for writing, a demanding and language related manual activity, should be one criterion to differentiate the four groups. The other criterion is innate handedness, which is of course not easy to determine with the current methods, although the two pure states (left- and right-handedness) are very different from each other. Either the right or the left hemisphere

[11]Nevertheless, switched right-handedness is observable: Sattler (2000, pp. 256-259, p. 262) reported some cases of switched right-handers who were mostly not coerced to left hand use, but changed hand preference in early childhood for various reasons (e.g., an admired left-handed grandfather as an ideal) on their own.

is dominant for motor activities and speech. A low degree of lateralization, instruction towards right-handedness, and learning from examples can cause that individuals do not demonstrate a distinct handedness but appear to be mixed-handed. Nevertheless, each individual is lateralized in one or another way and innate handedness exists but is concealed and potentially indeterminable. The correct classification of left-handers, right-handers, and SLHs is a practical but not a theoretical problem of handedness research and is a challenge for further experimental work.

Most of the following reviewed studies distinguished only two groups instead of the three (relevant) groups. The writing hand is often a criterion, which separates SLHs and left-handers but does not separate SLHs and right-handers. In other studies the hand preference, which is determined by questionnaires, is used as criterion. This latter criterion is fraught with two problems. The minor one is that nonswitched left-handers and SLHs, which are correctly identified as left-handers, are combined in one group irrespective of their differing writing hand, although it would be easy to discriminate both groups. The other more relevant problem is that many SLHs are classified as right-handers because of inappropriate questionnaire methods. It should be noted that a determination of right-handers as a pure group is impossible, as SLHs and right-handers are currently not distinguishable.

Following, the effects of shifting on motor skills, intellectual performance, spatial abilities, speech impairment, personality traits, scanning direction in visual perception and drawing direction, hemispheric asymmetry of neuronal activity, and physiological measures will be studied. Three findings can be inferred from the analysis. First, the three groups of different handedness (left-handers, SLHs, and right-handers) demonstrate a wide variety of behavioral differences among each other, which can be used to distinguish the groups. The considerations concerning a new test approach will benefit from this instance. Second, SLHs suffer from switched handedness. Adverse psychological consequences definitely exist. Third, the results provide indirect evidence for the alternative handedness model. Differences between LHWs and RHWs are comprehensible when it is regarded that many RHWs are SLHs. The apparent cognitive advantage of LHWs implies a small cognitive disadvantage of SLHs, compared to nonswitched right- or left-handed individuals. Finally, many differences are not explainable without the new model.

### 3.3.1 Motor Skills

Adapted from the alternative model of handedness I propose three theses regarding the motor skills of the preferred and nonpreferred hand in performance tests. First, classified left-handers (CLHs), which are perceived to be left-handed and are determined by questionnaires, self-reporting, or sometimes by writing hand, are more proficient with the left hand than the group of classified right-handers (CRHs) with the right hand. The CLHs group is also the more homogeneous group. The latter group contains a lot of SLHs who understand and use the right hand mistakenly as their dominant hand. As SLHs are among the CRHs it can be expected that on average CLHs perform better with their preferred left hand than CRHs with the right hand. By contrast, the nonswitched left- and right-handers should demonstrate equal skills.

The second thesis regarding the nonpreferred hand is more ambiguous. The best performing group in the performance test should be the SLHs because their nonpreferred left hand is, according to innate disposition, the more skillful hand. The mean performance of nonswitched left-handers can be expected to be better than the mean performance of right-handers because environmental requirements enforce left-handers to use their nonpreferred right hand for manual activities more often than right-handers are made to use their left hand. Therefore, the mean performance of CLHs compared to CRHs depends on the extent of the performance differences and on the ratio of SLHs and right-handers in the group of CRHs. Additionally, a higher incidence of individuals with poor performance with the nonpreferred hand can be found among CLHs than in the group of CRHs, irrespective of the mean performance of both groups. The poor performance of some right-handers with their nonpreferred hand is less noticeable as they are together with the better performing SLHs in the CRHs group.

Third, SLHs may generally have impaired motor skills (fine and gross and with hands and feet) caused by an overexertion of the brain, particularly of the left hemisphere. Sattler (2000, p. 49) reported fine motor problems and Sovák (1968, p. 221) found clumsiness in manual activities in 21.7% of 134 switched left-handed children. Such an effect would cause a better performance of CLHs with the preferred hand compared to CRHs and increase the probability that CLHs also perform better with the nonpreferred hand.

Three other facts may restrict the generalizability of the theses: First, in writing or activities similar to writing (e.g., dotting) right-handers could be faster than left-handers with the preferred writing hand because the writing direction from left to right gives them a certain advantage (sidedness bias of tasks). Second, when most CLHs do not write with the left hand, which was usual in Western countries until the 1950s (Beukelaar & Kroonenberg, 1986; Hugdahl et al., 1993; Tan, 1983) and is still usual in countries, which are conservative towards left-handedness (Hoosain, 1990; Ida & Mandal, 2003; Shimizu & Endo, 1983; Teng et al., 1976, 1979), they lack training of fine motor skills with the left (preferred) hand, which may limit the accuracy of the first thesis. In Western countries nowadays 80% to 100% of CLHs are writing with the left hand. Third, for some motoric undemanding tasks (e.g., picking up parts), which are often performed with either hand the differences between both groups (CLHs and CRHs) may be small.

Several studies confirm the proposed theses. Bishop (1980, 1984) reported that a higher ratio of children, which performed poorly with the nonpreferred hand, can be found in overt left-handers (CLHs according to the above definition) than in overt right-handers (i.e., CRHs). This effect was not ascertainable for the preferred hand. In an experiment where participants had to move small parts with tweezers (Perelle et al., 1981) LHWs showed a better overall performance. In six of eight experimental situations, in which either the preferred or the nonpreferred hand was used to carry out the task, LHWs outperformed RHWs. Also Kilshaw and Annett (1983, p. 260) found a general tendency that CLHs outperformed CRHs with both hands in a peg-moving test.

For five measures of manual skills (pegs, dots, dart throwing, marble shooting, and ball throwing) Steenhuis and Bryden (1999) reported a better performance of self-classified left-handers with the preferred hand in four tasks and with the nonpreferred hand in all tasks compared to self-reported right-handers. Based on the first thesis, a higher motoric proficiency with the preferred hand and a higher homogeneity of the CLHs group can be expected, which is confirmed by the results. A better performance with the nonpreferred hand is also consistent with the second and third thesis and also the idea that CLHs are favored compared to right-handers and SLHs. It must be taken into account that left-handers live in a right-handed world and are coerced to practice the right hand more often than CRHs the left-hand. Furthermore, impaired motor skills in SLHs could be a cause of the generally lower performance of CRHs with both hands.

As the *relative* performance difference between preferred and nonpreferred hand is in fact lower for CLHs than for CRHs, Steenhuis and Bryden (1999, p. 10) suggest that CLHs should be recognized as more weakly lateralized than CRHs. However, the *absolute* performance difference points at the reverse interpretation, which I regard much more convincing in this case. CLHs dominate CRHs with each hand and seem to be stronger lateralized with higher motoric skills of both hands.

Results from questionnaires may be a reason for an analogous interpretation of performance data. In preference questionnaires, CLHs often reveal that they are less lateralized than CRHs as they use the nonpreferred hand more often and the preferred hand less often compared to CRHs. A more frequent use of one hand means less use of the other. So, a weaker lateralization can be derived from the preference data. For performance data this procedure is dubious. A better performance of one hand is not accompanied inevitably with a lower performance of the other.

### 3.3.2 Intellectual Performance and Spatial Ability

Due to several above cited reports and studies (cf. Rett et al., 1973; Sattler, 2000; Sovák, 1968) it can be expected that shifts of writing hand may cause on average a reduced intellectual and cognitive performance of SLHs compared to left-handers and right-handers who are writing with their dominant hand. A difference in intellectual ability between innate and nonswitched left- and right-handers is not to be anticipated on the basis of the alternative handedness model. Switching the writing hand and not left- or right-handedness itself is the reason for differences between several groups of handedness, as will be shown in the subsequently reviewed studies on academic performance. It should be noted that these studies usually distinguish CLHs from CRHs and not innate left-handers from innate right-handers. Right-handers are usually not distinguished from SLHs. Nevertheless, three comparisons between SLHs and nonswitched left-handers, between left hand writing left-handers and CRHs, and between SLHs and CRHs are theoretically possible. The adverse impact of switching should be observable in SLHs and slightly also in CRHs as this group comprises SLHs, which are classified as right-handers. Probably more than 40% of all CRHs are actually SLHs.[12]

The following considerations are based on the assumption that the probability of a shifted writing hand at a certain time in a certain country is uniform for all left-handers, except for a group of approximately 10% with very low cognitive ability, and independent from their individual intellectual ability. As hand preference is often switched at an age between 3 and 8 years it seems unlikely that the decision of parents or teachers to educate a child to right hand writing depends on the level of cognitive performance,

[12] A frequency of 15% correctly perceived left-handers in a population causes 35% SLHs, 50% right-handers, and a ratio of 41.2% (→ 35%/85%) of SLHs among the CRHs. Five percent left-handers induce 47.4% (→ 45%/95%) of SLHs among the CRHs.

which is possibly unknown at that time. Criteria such as attitude against left-handers in a society, the parents' handedness, and reported or the parents' own experiences with left-handedness may be more relevant for the decision in favor of a right writing hand and the acceptance of a potential switching of the writing hand than the child's intellectual ability.

Only in cognitive disabled persons could the probability of hand switching be interrelated with intellectual performance. A higher degree of intellectual impairment may be accompanied with an increased observable left-handedness as individuals with mental handicaps may have a reduced level of attention or a limited ability to understand instructions (cf. 3.2.3 *Prevalence of Left-Handedness in Clinical Patients*).

Sovák (1968, pp. 237-240) compared the achievement of nonswitched left-handers ($n = 9$) and SLHs at school. The latter group was subdivided in *completely* switched (for all manual activities) left-handers ($n = 23$) and *partly* switched (for writing but not for drawing and other activities) left-handers ($n = 68$). Sovák reported a better performance of LHWs compared to SLHs. The marks (four grade levels) of the three groups and the switching status were not significantly independent, $\chi^2(6,\ N = 100) = 15.25,\ p < 0.025$ (own computation). Also the writing hand and the performance at school was not significantly independent when the completely and partly switched were combined in one group of RHWs, $\chi^2(3,\ N = 100) = 12.49,\ p < 0.01$ (own computation). The school achievement of completely switched children became more stable with increasing age as the first and second graders overall performed worse than third graders and above.

Douglas, Ross, and Cooper (1967) analyzed the performance in an achievement test at school of three groups with different handedness status. The children were assigned to groups of consistent right-handers ($n$ = 2,756), consistent left-handers ($n = 186$), and a group of inconsistent mixed-handers ($n = 311$). As more precise information is lacking, particularly with regard to writing hand, it can be assumed that the latter group is the group of SLHs. The other two groups of consistent handedness are understood as CRHs and CLHs (with right or left writing hand). The intellectual performance of the group with inconsistent handedness was slightly lower at the age of 8, 11, and 15 years than the performance of the other groups, which were nearly on the same level. The higher prevalence of inconsistent handedness among students with poor performance is remarkable (1 SD and more below average). The authors added that this result does not show an unambiguous causality between performance and handedness. The higher incidence of working class children, who generally do not do as well in the test, in the mixed-handed group may actually be the reason. The change of writing hand of 26 children between 6 and 11 years from right to left and of 19 children of the same age from left to right demonstrates the possible influence of a writing hand shift on cognitive performance. Those children who switched from right to left writing hand improved performance at school in successive tests at age of 8, 11, and 15 years. The other group showed a reverse trend in the three successive tests. These data confirm the hypothesis that SLHs are not doing as well as nonswitched left-handers, because of their switched writing hand. This conclusion is based on the authors' interpretation, which suggests that the first group changed to the preferred (left) hand and that the second group was forced toward writing with the nonpreferred (right) hand.

Crow, Crow, Done, and Leask (1998) classified students at school ($N$ = 12,770) according to their relative hand strength and found a distribution with 85% CRHs, 5% mixed-handers, and 10% CLHs. As 11.2% of the students were LHWs, it seems that the 10% CLHs are nonswitched left-handers. Many of the 5% mixed-handers are possibly SLHs with similar skills in both hands. The group with mixed handedness demonstrated the lowest cognitive ability in four tests compared to students with distinct handedness. The low intellectual performance of the mixed-handed group and of the weakly lateralized students in the group of CRHs suggests that those who have the greatest difficulties with the requirements of a right-handed world, especially with right hand writing, may be most harmed by the consequences of hand switching and therefore show the most impaired intellectual performance.

In arithmetic and English tests at school, switched left-handed Scottish students ($n$ = 14) performed significantly worse than 14 RHWs paired for sex, class, and intelligence (Clark, 1957, pp. 185-187). The performance comparison between 18 LHWs and 18 RHWs, as well paired for sex, class, and intelligence, demonstrated also a weaker achievement of left-handers but the difference was lower and not significant.

The analysis of data from the Medical College Admission Test in the US revealed a difference in academic achievement between LHWs and RHWs (Halpern, Haviland, & Killian, 1998). Among all test candidates 11.6% were LHWs, with a higher frequency of male LHWs (12.6% of all males) than female LHWs (10.4% of all females). Among the accepted candidates 13.5% were LHWs. The ratio of LHWs was also higher in successful males than in successful females (14.6% versus 12.1%). From all LHWs 24.8% were accepted compared to an acceptance rate of 20.8% for RHWs. Because of the large sample size of more than 150,000 candidates, the authors considered the sample as the complete population (of prospective medical students) and did not conduct statistical tests. LHWs also did better than RHWs in three of four subtests.

Comparable results were provided by Noroozian, Lotfi, Gassemzadeh, Emami, and Mehrabi (2002). They analyzed the acceptance rates and test scores of the college entrance examination for the national universities in Iran. About 10,000 candidates were randomly chosen out of the annually one million test participants for each of the 5 years (1993 - 1997). Information regarding writing hand, test score, and acceptance or rejection was available for a sample of more than 51,000 applicants. The acceptance rate for LHWs was 27.3% compared to 24.3% for RHWs. The difference is significant on a 99.99% level. Although the acceptance rates of LHWs in four different study areas were higher than the acceptance rates of RHWs, the differences were insignificant in three cases due to small sample size. Within all candidates 6.6% were LHWs (6.7% of all males and 6.5% of all females). Among the accepted applicants the share of LHWs was 7.4%. The mean examination score for LHWs of 5,060 was significantly better than the score of 5,020 for RHWs ($p < 0.002$). A hypothetical ratio of 43.4% SLHs, which brings the ratio of all left-handers to 50%, can be expected within the 93.4% RHWs. If a test score of 5,060 were to be assumed for all nonswitched left- and right-handers, a hypothetical mean score of 4,974 would be the result for SLHs. A lower ratio of SLHs would furthermore reduce this hypothetical score for SLHs. The difference of 86 points is smaller than the defined standard deviation of 100 points. So the difference is noticeable but not huge.

The studies by Halpern et al. (1998) and Noroozian et al. (2002) demonstrated a better academic performance of LHWs compared to RHWs. However, according to the new model, left-handedness should be neither an advantage nor a disadvantage. Therefore, the main reason for this outperformance of LHWs should be found in the writing hand and the switching of the writing hand. The group of RHWs consists of right-handers and SLHs. According to the results by Crow et al. (1998), Douglas et al. (1967), and Sovák (1968) latter group may perform poorer than nonswitched left- and right-handers. Even the poorer candidates, irrespective of writing hand and innate handedness, must probably have fulfilled some entry conditions for the test (e.g., high school diploma). Therefore, some homogeneity in performance is guaranteed. The relevant (but not enormous) differences of scores and acceptance rates in both studies are consistent with this consideration.

Other studies with an experimental design like the research by Halpern et al. (1998) and Noroozian et al. (2002) did not confirm an intellectual advantage of LHWs. This may be caused by an insufficient small sample size or a too high homogeneity of the sample. For example, a study on cognitive performance with 7,686 children who were in school grades 1 to 6, did not find relevant cognitive differences between groups of CLHs and CRHs (Hardyck, Petrinovich, & Goldman, 1976).

A more distinct performance difference between LHWs and RHWs could possibly be demonstrated with two other experimental designs. The first approach should determine the relationship between the different intellectual achievements of LHWs and RHWs and the homogeneity of a sample. I would expect a higher performance difference between LHWs and RHWs in more inhomogeneous groups (e.g., a representative sample of students at the age of 10) than in homogenous groups (e.g., college applicants) but such research is still to be carried out. A study, which pursues the second approach, should determine the ratio of LHWs (and SLHs if data are available) in groups of different levels of education or academic performance. I could not find a study, which followed the first approach, however some studies provided data regarding the second approach.

M. O. Wilson and Dolan (1931) determined handedness and possibly switched handedness of 2,328 sixth grade students. In two groups, which had been separated on the basis of cognitive ability and were approximately the same size, the frequency of left hand writing children was slightly lower in the higher performing group than in the lower performing group (higher section: 3.51%, lower section: 3.70%). The ratio of SLHs was much higher in the lower section (6.34%) than in the higher performing group (3.09%). The assignment of 84 LHWs (42 in each section) and 109 SLHs (37 in the higher section and 72 in the lower section) to the sections of lower and higher ability and their writing hand were not significantly independent, $\chi^2(1, N = 193) = 4.42$, $p < 0.05$ (own computation). The analysis with three groups of handedness status (CRHs, LHWs, and SLHs) also shows that handedness status and ability level are not significantly independent, $\chi^2(2, N = 2{,}328) = 13.93$, $p < 0.001$ (own computation).[13,14]

[13] As M. O. Wilson and Dolan (1931) and Sovák (1968) compared LHWs and SLHs it should be stressed that M. O. Wilson and Dolan's study corresponds better with the idea of the above proposed second experimental design. Only M. O. Wilson and Dolan drew a representative sample and determined two levels of cognitive performance, the handedness status of every participant, and the frequency of LHWs and SLHs in both performance sections. Sovák compared instead only SLHs and nonswitched left-handers. Both groups were specifically selected for this study and were not part of a larger representative sample of left-handers, right-handers, and SLHs. Nevertheless, Sovák reported an impressive result.

[14] In an exemplary study, which would implement the above suggested second experimental design, data on cognitive performance and writing hand (and switched hand use, if available) of a very broad and representative sample (e.g., children after finishing elementary school at an age of 9 or 10 years) would

Annett and Kilshaw (1983) examined the relationship between educational status and left hand writing. In a group of people with a higher educational status (college students), the incidence of LHWs was higher than in a more general population of school children, but the differences were not statistically significant for any sex or both sexes together.

The research on intellectual precocity (e.g., Benbow, 1986; Benbow & Benbow, 1984; O'Boyle & Benbow, 1990) found an elevated incidence of left-handedness in verbal and/or mathematical excellent youths compared to control groups, which are more or less comparable to the talented students, like parents, siblings, or less talented students. Such a consequence may also be caused by switching left-handers. Ratios of about 35% to 45% of the population are SLHs and these can be affected in their intellectual ability as a result of shifting. As this effect occurs on all levels of cognitive ability, even the most excellent individuals will be harmed when they are switched in writing hand. The frequency of unrecognized SLHs, which are classified as right-handers, is therefore expected to be lower in the group of the most precocious and the frequency of innate left-handers (and of innate right-handers) is increased. A comparison of the precocious group with normal youths suggests an apparent advantage of left-handers although actually SLHs are disadvantaged and emerge with a decreased frequency amongst the most talented. Furthermore, the frequency of male LHWs (14% to 24%) seems to be significantly higher than the frequency of female LHWs (7% to 20%). This sex difference is possibly caused by different degrees of cognitive impairment through hand switching in males and females. If switched talented females were less affected in their cognitive ability the ratio of female LHWs should be lower than the ratio of left hand writing males among the most intelligent youths. The ratio of shifted females among the precocious should be higher than the ratio of switched males. The slightly higher incidence of left hand writing in normal males compared to normal females cannot be the only reason for the sex difference among the talented. If 10% of normal males and 8% of normal females were LHWs, this would cause only 25% more left-handed males than left-handed females among the most excellent students. As the excess appears to be significantly higher (50% to 100%), an interaction of sex and handedness switching is proposed. The strength of intellectual disturbance due to hand switching should be different in both sexes.

Hardyck et al. (1976) reviewed studies on deficit and handedness and concluded "that

need to be collected. The population would be split into two or more performance groups, and the ratio of LHWs (and SLHs) in each group would be determined. Based on the alternative model and previous research, it can be expected that there are more LHWs in groups with an average performance level above the median participant, than in groups with a performance level below the median participant.

the hypothesis of no difference in intellectual and cognitive performance between right- and left-handed subjects can be accepted as true" (p. 278). The studies reviewed by Hardyck et al. can be differentiated in two types.

The first type analyzes whether a distinct feature can be found with different frequencies in different groups. The above quoted studies verified whether extraordinary intellectual achievement can be found more often in groups with a differing writing hand or hand preference. Many studies with participant numbers ranging from a few hundred to more than 7000 did not report a significant effect (cf. Hardyck et al., 1976). Larger samples are possibly necessary (cf. Halpern et al., 1998; Noroozian et al., 2002), or the degree of homogeneity of samples regarding the cognitive ability was not optimal to notice an effect.[15] Furthermore, in some studies it remains unclear, which of the students who are classified as left-handers, are switched or nonswitched in writing hand and/or in other manual activities. Two experimental study designs, with either differing homogeneity of subsamples, or with subsamples of different levels of education, were suggested above and both can be understood as subtypes of this first type.

Studies of this first type try to verify whether a switched writing hand or a switched handedness has an impact on cognitive ability. Both the extent of the pressure towards right-handedness and the ratio of SLHs are parameters, which influence the results of studies with such structure. Another aspect is that the strongest left-handers who might be most harmed by the negative consequences of hand switching are perhaps less often switched in liberal societies. This increases indirectly the performance of the remaining SLHs and of the whole group of RHWs. As LHWs are rare they could have a special motivation and demonstrate resistance against suppression and discrimination in a right-handed world. Therefore, they may perform better in ability tests. Another cause of a better performance of LHWs could be that parents with higher educational status do not only pass on higher education to their offspring, but also ensure more carefully that a left-handed child is not switched in writing hand. Both, the motivational influence and the educational influence are not quantifiable. The first one may exist in Iran but should be small in more liberal countries like the US, UK, or Canada.

Studies of the second type (e.g., Gordon, 1921; cf. Hardyck et al., 1976; Pipe, 1988) examine whether an increased prevalence of left-handedness or a noticeable distribution of handedness is found in a group of mentally impaired persons. Such studies did not analyze

[15]In a very homogeneous sample (e.g., the upper 5% percentile of high school graduates) the LHWs group and RHWs group, which includes SLHs, probably do not demonstrate significantly different cognitive skills. The sample is too homogeneous and the grades of both groups should be excellent.

the cognitive effect of switching hand preference or writing hand, but determined whether left-handedness can be more often found in such a population. As switching attempts are more often unsuccessful because of a lowered individual capability to conform to such attempts (cf. 3.2.3 *Prevalence of Left-Handedness in Clinical Patients*), the frequency of left hand preference is actually higher in clinical patients. Hence, the mental impairment is the reason for a lower switching rate in left-handers and is not the cause of a higher incidence of innate left-handedness among the cognitively disabled.

This comparison shows that both types of studies are dissimilar and the results regarding left-handedness depict two completely different effects: In the normal population a reduced intellectual achievement of SLHs and an increased frequency of LHWs in the group of the more successful is caused directly and indirectly by the switching of left-handedness, but the cognitive handicap itself is the reason for a lower switching rate and a higher rate of left-handers in the mentally impaired.

Beside cognitive disturbance a switching of the writing hand in left-handers can also cause impairment of spatial abilities. Next to several other switching consequences Sattler (2000, p. 49) described difficulties in spatial orientation and left-right-confusion. As the brain of left-handers is mirror-inverted compared to right-handers (but functionally similar) the switching may cause an overexertion of left-hemispheric areas, which are not responsible for speech and language production but possibly for spatial tasks, in SLHs. Although the neuropsychological processes and effects are unclear, I propose such a connection between spatial impairment and switched writing hand. A study with three groups of participants, LHWs, SLHs, and CRHs, provides some support to the idea that writing hand shifts may disturb spatial abilities (Ardila, Correa, Zuluaga, & Uribe, 1988). The participants were paired for sex (5 men, 3 women), age, and educational background and carried out the spatial relations subtest, which assesses the ability of mental rotation, of the Differential Aptitude Test (Bennett, Seashore, & Wesman, 1959). SLHs scored significantly lower than LHWs and CRHs. The latter group also outperformed the LHWs statistically insignificantly. Besides low mental rotation skills, SLHs demonstrated according to Ardila et al. “general difficulty in manipulating spatial information, in spatial orientation, in ordering numbers, in following routes, and in moving a car backward” (p. 149).

### 3.3.3 Speech Impairment

Authors with special focus on SLHs (Rett et al., 1973; Sattler, 2000; Sovák, 1968) reported unanimously that switched writing hand causes stuttering and stammering in many affected left-handers. My own computations with Ballard's (1911-12) data from a sample of school children indicate that stammering occurred significantly more often in SLHs than in the control group of children, which comprised of CRHs (99%) and LHWs (1%), $\chi^2(1,\ N = 13{,}189) = 29.32$, $p < 0.001$. In another sample Ballard compared SLHs and nonswitched left-handers and found a strong relationship between stammering and shifted handedness. Of 271 SLHs, 46 stammered at the time of inquiry and another 24 occasionally in their childhood. None of the 51 children who wrote with the left hand stammered. My own computations demonstrate that the connection of writing hand and stuttering was highly significant for those who stammered, $\chi^2(1,\ N = 322) = 8.76$, $p < 0.005$, as well as for the children who stammered at any time, $\chi^2(1,\ N = 322) = 15.35$, $p < 0.001$.

The analysis of two family pedigrees, each with five generations, also showed that stuttering and stammering is more often found in SLHs or ambidextrous persons, than in LHWs and RHWs without a history of hand preference shifts (Bryngelson & Clark, 1933). The authors concluded "that stuttering is brought into expression only when a naturally left-handed person is forced in infancy to use the right hand" (p. 388).

The idea that a switched writing hand could be a cause of stuttering has been disputed since this idea arose (compare for early reviews Travis, 1929; Travis & Johnson, 1934; and a more recent by Homzie & Lindsay, 1984). A contemporary critic put forward two arguments against the "'switching-causes-stuttering' myth" (Elias, 1998, p. 202) as he named the described connection. First, many studies did not verify that stuttering is related to switching attempts or left-handedness and second, many SLHs did not stutter, and stuttering could be caused by the violent and ruthless methods of switching and not by the switching itself.

Both arguments are inaccurate: The first argument fails because the quoted studies did not analyze whether switching increases the chance that SLHs develop stuttering (Porfert & Rosenfield, 1978; Webster & Poulos, 1987; cf. Records, Heimbuch, & Kidd, 1977). The researchers had neither directly nor indirectly distinguished between SLHs and nonswitched left-handers. Therefore, it is not surprising that causality between hand switching and stuttering could neither be confirmed nor disproved. The experimental approach was quite inappropriate and ignored hand switching as an important and relevant factor and as a potential reason for stuttering. The studies determined more whether stuttering is more frequent in left-handers than in right-handers and did not find such evidence, but this is definitely less than Elias (1998) asserted. The association between hand switching and stuttering could be disproved by differing results or null results in studies with the same design as Ballard (1911-12) used. Such studies are still missing today.

Also the second argument is flawed: More than 70 years ago Travis and Johnson (1934) pointed out that a study, which demonstrates normal speech in SLHs, is irrelevant because the proponents of the switching-causes-stuttering hypothesis do not claim that all or most SLHs (and nonswitched left-handers) stutter, but that shifting handedness raises the possibility of stuttering. Even Ballard (1911-12) reported that 201 of 271 SLHs never stuttered.

Furthermore, the critics of the hypothesis that shifted writing hand and stuttering are linked reveal another misunderstanding. It has not been proposed that the switching of the writing hand is the only reason for stuttering, but it was claimed and confirmed in several studies that shifting hand preference is at least one cause of stuttering. A violent method of switching may have additional adverse consequences.

Switching itself seems to be a more important reason for disturbances like stuttering than the method of switching. The relationship between stuttering and left-handedness should be seen as an association of cause (switched left-handedness) and consequence (stuttering). Altogether, a well-founded conclusion is that switching the writing hand may cause a permanent overstrain of the nondominant left brain hemisphere and difficulties in brain specialization in many left-handers. Although the etiology remains unclear, a link between stuttering and incomplete hemispheric organization and lateralization, sometimes in combination with motor disturbances, has been discussed for decades (Orton, 1937). Such a lack of hemispheric organization may be caused by handedness shifts in individuals who were never recognized as left-handers. Shifts in hand preference especially in writing hand, can be one reason among others for stuttering, or in other words: "Nevertheless, it is interesting to contemplate the possibility that forced right-hand training is one of several factors that put *certain* left-handed children at risk for speech problems" (Harris, 1992, p. 192).

Impairments of speech related functions and its connection with handedness, writing hand, and unilateral cerebral lesions were studied by I. Gloning, Gloning, Haub, and Quatember (1969) in 57 matched pairs of different handedness. The matching criteria were size, location, and type of cerebral lesion. All of the 57 left-handers were forced to right hand writing at school but 17 of them later changed to the left writing hand. The remaining 40 SLHs continued right hand writing after finishing school. The other 57 individuals were writing with the right hand and therefore were understood as right-handers (CRHs according to my terminology). They were selected from a larger group of CRHs. Thirty-two pairs had a left-hemispheric lesion and 25 had a right-hemispheric lesion. Regarding age, sex, and years of schooling left-handers and CRHs were not significantly different.

I. Gloning et al. (1969) rated the patients' performance in eight language related behavioral functions like verbal comprehension, expressive language (form and content), naming, writing, and reading. The rating scale extended from level 1 (*no disturbance*) to level 5 (*maximal disturbance*, *loss of function*).

A pairwise comparison of patients with left-hemispheric lesions showed that speech impairment was slightly but insignificant stronger in CRHs than in left-handers (6 LHWs and 26 SLHs). Right-hemispheric lesions caused more severe and significant impairment in most left-handed persons (11 LHWs and 14 SLHs) compared to the matched CRHs. The first result can be understood in two ways. Either a writing hand shift causes left-hemispheric speech function in SLHs (cf. Siebner et al., 2002), or some persons among the CRHs are unrecognized SLHs and are therefore more or similar impaired than the matched left-handers. Both explanations are consistent with the vague results of the pairwise comparisons. The second result indicates that the right hemisphere has a more important function for speech in left-handers, even in SLHs, than in CRHs.

Further comparisons within the group of the 57 left-handers showed results, which confirm on the one hand the theory of right-hemispheric speech in left-handers and on the other hand the assumption that switching handedness may change the lateralization of speech. For this analysis the levels of impairment were aggregated in two groups: Weak impairment (levels 1 and 2) and strong impairment (level 3 to 5).

Most comparisons of the four subgroups (LHWs and SLHs with either left or right lesion) were not significant. SLHs with left or right lesions differed significantly among each other in writing, reading, and calculating performance. Those with left lesions, contralateral to the writing hand, were more strongly impaired. This result suggests that the switching of the writing hand is causal for the existence of speech and language related functional areas in both hemispheres of SLHs (cf. Siebner et al., 2002). In other words: Switching matters, because it influences and changes lateralization of speech and language. A comparison of two groups with lesions either contralateral to the writing hand (11 LHWs with right lesion and 26 SLHs with left lesion) or ipsilateral to writing hand (6 LHWs with left lesion and 14 SLHs with right lesion) also identified significant stronger disturbances in writing, reading, and calculating in those patients with contralateral lesion. This illustrates that the writing hand is, despite an innate lateralization of speech an important factor, which influences lateralization. In other words: Writing hand (either left or right) is relevant for the lateralization of speech and language.

Another striking difference between the four groups of left-handers is the occurrence of transient aphasia. Such a recovery is found in nearly half of all SLHs with right brain lesion (6 of 14) but was uncommon in all other groups. The result is not surprising as the SLHs with right-hemispheric lesion are the only group with two speech and language related areas and a lesion ipsilateral to the writing hand. Therefore, it can be expected that the left hemisphere, which is responsible for writing, functionally replaces the right hemisphere although this is the hemisphere, which is inherently concerned with motor dominance and speech. Only for the group with switched handedness and right-hemispheric lesions can be an immediate change of speech and language related areas and a fast recovery from aphasia expected.

On the other hand, SLHs are more threatened to acquire aphasia through a brain lesion as they have two hemispheres, which are speech related, and a lesion of either could cause aphasia. In a subsequent analysis of data of the 57 pairs of dissimilar handedness K. Gloning (1977) reported that significantly more patients with aphasia were found among the left-handers (48 of 57) than among CRHs (26 of 57). SLHs seem to be affected more often by aphasia but are sometimes less severely affected (cf. Harris, 1992, p. 194). In LHWs who have never written with the right hand, such an effect of more frequent but less severe aphasia should not occur. Further research is necessary on this matter. One condition for such research is an adequate number of LHWs. This requirement was not complied for a long time in Germany and Austria and probably not when I. Gloning et al. (1969) carried out their study.

Overall, the results presented by I. Gloning et al. (1969) can be understood in a way that speech is originally right-hemispheric in left-handers (either switched or nonswitched) and contralateral to the writing hand in everyone. Therefore, SLHs may have speech lateralized in both hemispheres (cf. Siebner et al., 2002) and LHWs only in the right hemisphere (cf. Longcamp et al., 2005). To be satisfied with the conclusion that the data by I. Gloning at al. indicate a weaker and more bilateral lateralization of speech in left-handers means to misjudge the value of this data.

A study by Goodglass and Quadfasel (1954) includes a data-set, which facilitates conclusions about lateralization of speech in left-handed aphasic patients (Table 1, p. 525). Based on the sidedness of unilateral lesions and incidence of aphasia, they proposed that speech is left-hemispheric when lesions are left-sided and aphasia occurs or when lesions are right-sided without an appearance of aphasia. For right-hemispheric speech the opposite is true. Considering the suggested connection of lateralization of speech and the writing hand Goodglass and Quadfasel determined for SLHs a tendency toward left-hemispheric speech (20 of 35 SLHs have speech left-sided) and for nonswitched left-handers a tendency toward right-hemispheric speech (right-sided in 10 of 15 LHWs). Unfortunately for nearly 60% of 123 patients the information about the writing hand was not reported. According to the above classification rule this group demonstrated by majority left-hemispheric speech (40 of 73). It should be remarked that the cases were collected in a period (1866 - 1954) when even for recognized left-handers right hand writing and right hand preference were much more the norm than today.

The theory of innate lateralization of speech and the influence of writing hand shifts on lateralization of speech can be verified with data by Cameron, Currier, and Haerer (1971). The data-set comprised of literate ($n = 37$), semiliterate ($n = 14$), and illiterate ($n = 14$) patients with left-hemispheric lesions. Only 3 of 65 patients were classified as left-handers. It is not reported whether they were literate and which hand they used for writing. The other 62 patients are classified as right-handers. As writing hand matters for the lateralization of speech, irrespective whether individuals are switched in hand preference or not, a difference in lateralization of speech between literate, semiliterate, and illiterate persons should exist under the assumption that not all CRHs are innate right-handers but some of them are unrecognized SLHs.

Due to the above considerations left- and right-handed literate patients with a right writing hand should develop speech and language functions in the left hemisphere. Regarding illiterate patients it can be expected that left-handers have exclusively right-hemispheric speech. Also in semiliterate SLHs speech should be more right-hemispheric than in literate SLHs. As speech in literate patients is more left-hemispheric than in semiliterate or illiterate patients, a lesion of the left hemisphere should cause aphasia more often in literate patients than in semiliterate or illiterate patients when all three groups contain a relevant number of unrecognized left-handers. Such a relationship between degree of literacy and frequency of aphasia was pointed out by Cameron et al.

(1971). Seventy-eight percent of the literate were aphasic. In the semiliterate group 64% were aphasic and only 36% of the illiterate suffered from this disturbance. My own computations demonstrate that aphasia and literacy were significantly not independent, $\chi^2(2,\ N = 65) = 8.28,\ p < 0.02$. It should be mentioned that this interpretation implies that some CRHs are actually SLHs. Otherwise the alternative theory of handedness cannot explain the connection between degree of literacy and frequency of aphasia.

Some of the above presented results depend on the assumption that lesions and aphasia are directly associated. For example: When a left-hemispheric lesion leads to aphasia the accepted conclusion is that speech is left-hemispheric. However, this is an incomplete analysis. It is not only important which side is damaged but also how the nondamaged rest of the brain copes with the demands. Or in words contributed by Nielsen to a discussion (cf. Roberts, 1951):

> Now, the lack, the loss is due to the lesion; but what that patient says is not due to the lesion. That is due to how well the rest of the brain performs and, of course, when it does not perform well, which it does not (otherwise the patient does not have aphasia) that means the area which is taking over has not entirely succeeded in taking over. (p. 48)

It should be added that the success of taking over might depend on previous writing behavior and hand preference. Aphasia caused by a lesion does not only reflect innate lateralization of speech but also the influence of a switched handedness on this lateralization.

### 3.3.4 Personality Traits

Idiosyncratic behavioral and personality characteristics of SLHs, mostly of school children, like restlessness, poor concentration, aggression, depression, feeling of inferiority, lack of assurance, seclusion, defiance, or emotional problems with neurotic and/or psychosomatic symptoms are reported by Rett et al. (1973), Sattler (2000), and Sovák (1968). Young and Knapp (1966) compared the personality of left-handed boys in three cities in Italy, who were completely forced to right hand preference including writing, but were classified as left-handers, with the personality of Italian-American left-handed boys in Boston, who were not forced to right hand writing. The left-handers and four control groups of CRHs (in Boston and in the Italian cities) were tested with the Cattell High School Personality Questionnaire. The switched left-handed Italian boys were significantly more demanding, impatient, subjective, dependent, and hypochondriacal than the

American left-handers and the control CRHs. Such traits are regarded by Cattell of being associated with neuroticism but not with anxiety. The neuroticism factor is considered as being affected by the environment. Young and Knapp referred to the negative appraisal of left-handedness and the rough procedure of shifting handedness in Italy as causes of the personality differences. Besides the method of switching and the low reputation of left-handedness, the switching itself may cause a permanent disturbance of the brain and the deviation of behavior and personality of SLHs from peer group average.

### 3.3.5 Scanning Direction in Visual Perception and Drawing Direction

Research on visual scanning and recognition suggests that the scanning direction depends on two factors. The handedness of an individual is one characteristic, which may influence the direction. The reading and writing direction of a language is another feature, which could determine whether visual scanning is either from left to right or from right to left.

Two studies on the perception of facial affects by Sakhuja, Gupta, Singh, and Vaid (1996) and Vaid and Singh (1989) showed that reading habits of Hindi and Urdu speakers and handedness affect the direction of visual perception. Hindi is written and read from left to right like Western languages with Roman alphabet. Urdu is influenced from Arabic script. The direction of writing and reading is from right to left in Urdu and in Arabic. In oral communication Hindi and Urdu are practically identical (cf. Vaid, 1995). Readers of Hindi perceived faces with smiles in viewers' left visual field happier than faces with smiles in the right visual field. Readers of Urdu demonstrated a contrary preference.

A plausible interpretation of this result is that participants scan or *read* pictures from one side to the other although they do not contain any verbal content. Hindi readers for example would start at the left and look at the left half of a face more intensively than at the right half. The information contained in the left half of a face (irrespective of whether the face is smiling or not) has a stronger effect on the overall impression than that in the right half of the face. According to this interpretation, Hindi and Urdu readers have shown differing scanning direction of nonlinguistic material in the experiment. The direction seems to be strongly influenced by the direction of reading.

Additionally, the authors of one study found a handedness effect (Sakhuja et al., 1996). Left-handers (i.e., CLHs) showed a trend toward a rightward scanning direction and right-handers (i.e., CRHs) toward a leftward scanning direction. Illiterate Hindi/Urdu speakers did not demonstrate any preference. The handedness effect was smaller than the effect of the script direction.

The results of other studies with Hindi, Urdu, and Arab readers suggest that pictures or drawings get a direction, which is influenced by reading habits as well as by handedness, while the drawing is being made (Vaid, 1995). The participants of a first study (all classified as right-handers) were asked to draw figures (bicycle, elephant, profile). The facing of the objects was most different between Hindi and Arab readers. A majority of Hindi participants faced the objects to the left. Arab readers preferred a rightward direction. Urdu readers with some knowledge of Hindi drew the figures more often facing to the left, but less often than the Hindi writers. As Hindi and Urdu readers were both from New Delhi, there could have been a common cultural influence toward a leftward preference. Other factors like pictures and drawings in newspapers, magazines, advertisements, TV, or cinema could be more relevant for the script direction and constitute the similarity of facial orientation. The author reported that a follow up study with Hindi and Urdu readers of differing hand preference found a handedness effect. In line with previous findings right-handed Urdu and Hindi readers (i.e., CRHs) differed among each other. Right-handed Hindi readers showed a more leftward direction of figures than right-handed Urdu readers. The interesting result is that the differing reading directions of LHWs did not affect the facing of their drawings. Both left-handed Hindi and Urdu readers oriented the drawings to the right. Less than 25% of their drawings were leftward oriented.

Martin and Jones (1999) reported a handedness effect in a study on face recognition. In several experiments they tested recognition of CRHs and CLHs and found that CRHs are more likely to remember faces correctly with a leftward direction. CLHs demonstrated a better recollection for right-facing portraits. As the face contains the important information of a portrait, such a result suggests an interpretation like the above quoted studies. Participants scanned or read pictures from one side to the other. Left-handers for example start at the right and look at the right half of a face more intensive than at the left half. Therefore, it is more likely that left-handers remember a rightward face correctly.

Finally, all these studies on the connection of handedness, script direction, face recognition, and orientation of drawings suggest that individuals have a preferred direction in visual perception, which is influenced by two effects. One factor is innate and connected with handedness. Left-handers scan visual information from right to left and right-handers vice versa. A second cultural factor is the script direction. Both factors interfere with each other. The cultural factor seems to be stronger than the innate factor.

The above mentioned group of authors also analyzed the relationship between handedness, stroke direction in drawing, and script direction (Vaid, Singh, Sakhuja, & Gupta, 2002). Two groups of handedness (CRHs and CLHs) were recruited as participants. In each group were the same number of Urdu and Hindi writers and a control group of illiterate Hindi/Urdu speakers. The participants were asked to draw figures (e.g., hand, arrow, and fish) and the stroke direction (left to right or right to left) was noted. The performance of the illiterate group suggests an innate preference, as stroke direction was the opposite in CRHs and CLHs. Illiterate left-handers performed the task more often in the biomechanical more favorable direction from right to left. Illiterate right-handers favored the inverse direction. Beside handedness the writing direction is another important factor. LHWs performed irrespective of the script direction the task more often in the favorable direction from right to left. The literate CRHs were influenced by the script direction of their language. A majority of right-handed Hindi readers draw from left to right. Urdu readers draw in the inverse direction. Finally, the comparison of two groups suggests that left-handers are more influenced by innate factors and less influenced by the environmental framework: Left-handed Hindi writers draw from right to left although the script direction in Hindi is from left to right. Right-handed Urdu writers draw in the same direction as they write (right to left) and not in the biomechanical more favorable direction from right to left. This study presented a cultural effect (script direction) and an innate effect (hand use or handedness). It would be interesting to know whether the latter effect is only biomechanical or whether it is also associated with visual perception and scanning direction like the above discussed research works.

### 3.3.6 Hemispheric Asymmetry of Neuronal Activity

Studies on lateralization of speech and language (Longcamp et al., 2003, 2005; Siebner et al., 2002) demonstrated that brain activity while writing or reading is asymmetric and mirror reversed in left-handers compared to right-handers. During hand motor tasks left- and right-handers also had differing neuronal activity in both hemispheres (Amunts, Jäncke, Mohlberg, Steinmetz, & Zilles, 2000; Klöppel, van Eimeren, et al., 2007; L. N. Singh et al., 1998). Due to these results it can be assumed that a fundamental functional and structural hemispheric asymmetry between nonswitched left- and right-handers exists.

Two studies by Siebner et al. (2002) and Klöppel, Vongerichten, van Eimeren, Frackowiak, and Siebner (2007) showed that this asymmetric and mirror reversed functional and structural organization of the brain can be changed and influenced by switching handedness, especially by switching the writing hand. Switching handedness causes increased brain activity in some areas of the nondominant left hemisphere but other areas in the dominant right hemisphere remain responsible for certain activities. Therefore, it can be expected that brain activity of SLHs differs from brain activity of nonswitched left- and right-handers in a specific way. Siebner et al. reported that switching the writing hand comes along with abnormal brain activity. SLHs demonstrated not only neuronal activity in the right hemisphere (like nonswitched left-handers), but a bilateral activation of the cortex.

Klöppel, Vongerichten, et al. (2007) studied movement-related neuronal activity while participants (16 SLHs, 16 left-handers, 16 right-handers) performed hand movements with right and/or left index fingers. The striking result of this study was again that SLHs showed inconsistent brain activity. On the one hand, the activity of the executive sensorimotor areas depends on the preferential hand use. The more frequent use of the right hand induces that areas in the nondominant left hemisphere are more involved in motor control than areas in the right hemisphere. On the other hand, higher-order sensorimotor areas are invariant. Despite preferential hand use and right hand writing for decades, these areas cannot be switched to the nondominant left hemisphere but right-hemispheric areas remain more active in SLHs.

### 3.3.7 Physiological Measures

In the early days of experimental psychology some physiological measures were analyzed in handedness research. The following quoted studies suggest that switching the writing hand may influence physiological variables, which can be measured.

Orton and Travis (1929) determined neuromuscular *action currents of voluntary and simultaneous contraction* of both hands and compared the reaction time. Orton and Travis showed that nonstuttering right-handers had, by majority, a right leading hand. The stuttering RHWs had a left leading hand.[16] Therefore, the authors suggested that the actual motor facilities of stutterers could be a consequence of training and might not represent the innate disposition. They conclude, “this envisagement fits nicely with the clinical observations of the relationship of stuttering to enforced shifts of handedness in writing in young children” (Orton & Travis, p. 67). In an experiment, which need not be discussed here in detail, Travis and Lindsley (1933) measured action currents, analyzed

[16] Unfortunately the authors did not have left-handed participants. The results were quite interesting.

the relationship between stuttering and handedness and achieved a similar result to the above, which was that stuttering and nonstuttering right-handers differed significantly with respect to the measured variables. The measures for nonstuttering right-handers and the left-handed control group also demonstrated clear differences.

Travis and Herren (1929) compared voluntary and simultaneous hand/arm movements in contrary directions (abduction and adduction) and recorded the leading arm (*kymographic records of simultaneous antitropic movements*). Participants comprised six groups: (group a) Nonswitched, nonstuttering left-handers, (group b) right-handed stutterers with unknown history of handedness, (groups c-f) right-handed stutterers and nonstutterers either with a history of left-handedness (i.e., SLHs) or with a history of right-handedness. Travis and Herren determined the same right leading hand for left-handers and all three groups of right-handed stutterers, irrespective of history of handedness. Right-handers with normal speech and history of right-handedness had a left leading hand. For right-handers with normal speech and a history of left-handedness a distinct leading hand was not found. The authors concluded "that right-handed stutterers differ materially from purely right-handed normal speakers in regard to motor leads as determined.... right handed stutterers are similar to purely left-handed normal speakers when compared on the basis of the determined motor lead" (Travis & Herren, p. 493). Thus, the study provided results, which are similar to the results by Orton and Travis (1929). Furthermore, the authors concluded "that in many stutterers the motor facility, as determined by training, is out of harmony with the native physiologic leads" (Travis & Herren, p. 493). The authors emphasized that it was beyond the scope of the study to explain why the two nonswitched groups of left- and right-handers had a nondominant leading hand (p. 493).

# 4 Alternative Approach of Testing Handedness

In this section I suggest an experimental approach to determine innate handedness according to the above concept. The framework of testing (items and participants) will be discussed and six classes of test items will be proposed. The new approach shall indicate how it can be ensured that testing is valid and reliable by means of different methods of testing, item selection, and test design.

An advanced method of testing, which is based on the new approach, does not exist at present and still needs to be developed. Therefore, results from experiments will not be presented in this section.

The main objective of testing is to determine the distribution of human handedness and to examine whether the current 10:90 ratio of CLHs and CRHs is innate or whether it is the consequence of a sociocultural bias in favor of right-handedness. Both item selection and test design have to consider the fact that daily practice makes the group of right-handers more homogenous and the left-handed group more inhomogeneous. This is true at least regarding a group of socially controlled activities as there are many requirements and incentives to perform activities with the right hand, even if someone is a left-hander. Switched and nonswitched left-handers practice a lot of manual activities with the right hand, but I expect that a remnant of left-handedness exists in every left-hander irrespective of whether she or he is shifted or not.

This latent left-handedness should be found in activities, which are not under social control and where right hand performance is not actively enforced. Appropriate items should be found and included in tests. Brain imaging is another promising method to discover unrecognized left-handedness. The expectable evidence that left- and right-handedness is innate would finally disprove all environmental theories (cf. Hertz, 1909/1960; Provins, 1997).

Additionally, an alternative test approach has to ensure validity and in particular ecological validity. Traditional handedness questionnaires do not fulfill such demands. Ecological validity of questionnaires is questionable as most human manual activities are without tools (cf. Marchant et al., 1995) but questionnaire items ask for tool use. Handedness is currently defined and measured as tool use preference and validity is sacrificed in favor of reliability. Outside criteria, which approve the questionnaire approach of measuring handedness, do not exist. More effort should be made to find external criteria and to demonstrate that these criteria are accurate.

The framework of testing (e.g., selection of participants and items) and the content-based selection of items will be considered next. Some items, which seem to be appropriate for determining handedness, will be presented and classified.

As part of the technical framework, further testing should be done without questionnaires and handedness should be determined only through performance tasks. Generally it should be routine to record the writing hand and, if available, information about successfully and unsuccessfully shifted hand preference especially for writing. Furthermore, the eight variables (four technical and four content related) for the analysis of laterality of function (Marchant & McGrew, 1991; McGrew & Marchant, 1994) provide helpful ideas to prepare an alternative handedness test for humans.

Among the more technical variables *context* (captive or wild animals) is irrelevant for humans. A sufficiently large *sample* size should be more easily achievable in experiments with humans than in experiments with nonhuman primates. Repeated *trials* (number of trials per subject per task) are desirable but are somewhat difficult to realize as human participants may get an idea about the purpose of a test when it is repeated. This could impair the results. Regarding the *age* it remains unclear whether children or adults are more suitable participants. Because of age, experience, and intellectual comprehension children are probably less influenced by a cultural or social norm. On the other hand, their motor skills are not completely developed. Three other variables, *function* (which organs, i.e., hands, arms, or feet, are observed), *task* (induced or spontaneous), and *complexity* (degree of difficulty or intellectual demand of tasks) are more content related and associated with item selection. The last variable *number of tasks* depends somewhat on the number of appropriate items (and the available time for testing).

Besides the technical criteria some content-based criteria should be considered regarding item selection. Self-observation and self-assessment are not required as participants exclusively should be observed. The items should be picked from a wide pool of human motor behavior. The focus is on the performance of tasks and spontaneous behavior in everyday activities in the real world. This motor behavior is mostly not instructed but more or less acquired in a self-contained process.

Items are unsuitable when activities are subject to a social norm, which demands or demanded an execution with the right hand now or in former times (e.g., writing or eating with cutlery), or when activities are performed with tools (e.g., scissors). Also fine motor activities (e.g., throwing, brushing one's teeth, or using tweezers), which are possibly influenced by other fine motor activities with enforced right hand preference (e.g., writing), are not suitable.

The new items should be based on motor activities with which a person makes oneself comfortable (folding arms), moves and stabilizes the body (stepping into a sack, sitting cross-legged, or standing up from kneeling), or solves a motor task (turning a few pages of a book or putting on a T-Shirt). Another desirable feature of a new test would be that the items are performed not only with one hand and an object but bimanually, without any tool or object, with the feet or legs, or with the entire body.

Each new item should be performed in one of two mirror reversed types. The above quoted items are examples for such tasks. These and other possibly more complex tasks do not have a bias of the kind that either a left-handed or right-handed procedure is more favored or socially more desired. Nobody makes an effort to show someone else how to perform these activities or instructs a special sidedness. Young children often perform such tasks even before they are instructed and advised in fine motor activities, which are often under social control and have a norm of right hand execution.

Without prior testing it is not obvious for most of the new items, which mirror-inverted version is associated with left-handedness and which with right-handedness. This must be determined through experiments. It is even possible that an item is unrelated to handedness. Based on two main elements of the alternative handedness model (innate brain asymmetry and dominant hemisphere is responsible for motor activities and speech) the fine motor control and motor behavior is expected to be more skilled on one side of the body, regardless of any amount of practicing and training of the limbs on the other side of the body. The aim of the alternative handedness test is to make sure that learned and acquired behavior and innate motor features can be distinguished from each other. The eventual measured behavior should be based on disposition (innate handedness) and not on plasticity of the brain (tool use preference as a consequence of potential influence and switching).

The items, which seem possible and appropriate to be used in the new test, are assigned to some classes of items in the following. Based on some published studies (e.g., Davison, 1948; Marchant et al., 1995; Rett et al., 1973), own unpublished experiments, and further considerations I suggest six classes of items.

1. The *motor asymmetry items* include some manual activities, which are common even for young children, like opening a bottle, clapping hands, putting on gloves, turning a few pages of a book, cracking and eating peanuts, holding a telescope in front of one eye (actually a card box tube in the experiment), drumming a rhythm, or shaking the head (cf. Bethe, 1933). A handedness test by Davison

(1948) contains some other possibly useful tasks like wiping dishes, using a shovel, or winding a string around a ball. Marchant et al. (1995) provided a long list of limb movements, mostly without tools or other objects, like carrying, reaching, eating, gesturing, holding, or touching. Such nontool activities are performed more often than tool use activities as Marchant et al. demonstrated. All nontool activities together are performed with the left and right hand with approximately equal frequency (cf. 2.2.7 *Alternative Methodology of Testing*).

Postural activities and body movements, especially for stabilization, are also part of this class. This includes tasks like putting on a T-Shirt, stepping into a sack or pants, climbing up stairs (infants initial step onto each individual step on a staircase is typically with the same leg), sitting and laying down on the floor and standing up (which hand is the supportive hand), stepping on a medicine ball with both feet (which is the first one), or spring-like running (which is the starting leg; can children change the jumping leg or do they prefer to jump with one distinct leg).[17] The standing position in sports like boxing, karate, taekwondo, or judo (cf. Mikheev, Mohr, Afanasiev, Landis, & Thut, 2002) or the turning behavior (cf. Mohr, Landis, Bracha, & Brugger, 2003) may also be related to handedness.

The sleeping position (left side, right side, on the back, or on the stomach) might be particularly for children another possible item in a test. Boynton and Goodenough (1930) determined the sleeping posture of nursery school children and the time slept in each position. The authors reported a positive correlation (0.53) between the strength of right-handedness and the amount of time spent sleeping on the left side and a correlation close to zero between strength of right-handedness and the amount of time spent sleeping on the right side. As all 23 children were classified as right-handers, I would be cautious of the numerical results although I agree with the inference that "the general tendency is to leave the preferred hand free

[17] The "riding" of the knights in the movie "Monty Python and the Holy Grail" is also an asymmetric form of locomotion: One thigh is lifted a little, the foot of this leg is half a step in front of the other and only the toes touch the ground. The knights, who do not have horses in this movie due to the movie budget, are jumping forward in this position, which looks a little bit like a running horse. Squires are coming behind and are imitating the clatter of hooves with two halves of a coconut.

I do not know whether this item provides any insights about the handedness of a participant of a test when doing this type of locomotion, but I strongly suggest checking it. Two questions should be answered: Does a person prefer one of the two mirror reversed versions of this "riding"? Is the preference for one version correlated in any way with innate handedness or with a preference demonstrated in other items?

during sleep rather than to assume a posture which would inhibit its movements" (Boynton & Goodenough, p. 274). Without knowledge of any test I would suppose such a tendency, which could probably be found in children at an age before hand switching takes place and potentially even in adult SLHs.

2. *Fatigue evoking tasks* are another item class. For example, Rett et al. (1973) examined diadochokinesia. In this activity hands are held in a "hands up!"-position and hands and forearms are turned along the forearms longitudinal axis alternately in both directions (inside and outside) to the end position. Rett et al. reported that earlier emerging fatigue of one arm was a good indicator (90% accordance with other tests) for the nondominant hand. According to Rett et al. one forearm and hand is turned faster, more accurately, and to wider end positions after a short time. After some minutes and with increasing fatigue, the dominant hand is clearly noticeable (Rett et al., pp. 46-47). This test could be a good indicator for handedness, particularly for children who are not yet at school, do not write, and have less training of fine motor skills than adults.

3. *Coordinative tasks* with combinations of several limb movements can also reveal superior motor skills on one side of the body. The turning of both forearms in the elbow joint and the simultaneous turning of both hands in the wrist in the same or the reverse direction is one of the more simple tasks. Other tasks may include combinations of steps (e.g., spring-like running or jumping like the Monty Python's "Knights of the Holy Grail") and arm movements or arm turnings. It is of interest whether complex movement combinations break down more often or more quickly on one side of the body. A relationship between unilateral coordinative skills and handedness is suggested and should be studied.

4. Two *physiological measures* (*action currents of voluntary and simultaneous contraction* and *kymographic records of simultaneous antitropic movements*) used by Orton and Travis (1929) and Travis and Herren (1929) might be helpful items in combination with other tests. Regarding action currents (cf. Orton & Travis), I would expect that such an experiment may disclose a suppressed innate motor preference, which is already existent on a neuronal or muscular level, but not observable in motor behavior. Such a remnant of left-handedness was reported in a brain imaging study (Siebner et al., 2002, p. 2816). They found both right-hemispheric and left-hemispheric activations of motor areas in SLHs while they were writing with

the right hand.

5. As the alternative model of handedness implies a connection of hand dominance and lateralization of speech, which is based on the idea of a consecutive evolutionary development of both, one or more items should examine a *connection of speech and manual activity*. Research by Kimura (1973a, 1973b) and reports from participants in some of my own experiments suggest such a relationship. I found that left-handers use the left hand significantly more frequently than the right hand for gestures while talking. It is unclear whether such a result is of general validity or whether special conditions caused such a finding. Further research is necessary and the topic would be worth investigating.

6. Differing handedness may not only cause asymmetries in motor behavior or motor skills but also in tasks with *mental left-right differences*, in *spatial imagination*, or in *spatial problem solving*. The studies by Martin and Jones (1999), Sakhuja et al. (1996), Vaid (1995), and Vaid and Singh (1989) suggest a different scanning direction in left- and right-handers. Their results indicate that spatial cognitive processes occur in two mirror reversed patterns. Left-handers probably analyze spatial problems or spatial information more easily from right to left than in the other direction. This approach is speculative but previous research has hinted, this may be worth investigating in more detail.

For the inclusion of an item in one of the six classes it is fundamental that the performance of a task depends on the innate disposition and that the item demonstrates (a) a better motor control of the limbs on one side of the body, (b) a preferred asymmetric version of body movements, or (c) another psychological or physiological feature, which is related to innate handedness. At present, for many possible items it is unknown whether an item is related to handedness at all and which asymmetric version refers to left- or right-handedness. To reach high validity in a new handedness test a large number of items should be examined as it may become obvious during the development process that the asymmetric execution of an item is random and not related to handedness. This would implicate the elimination of such an item.

Recent brain imaging studies showed a connection between handedness and lateralization of speech. Speech is right-hemispheric in left-handers, left-hemispheric in right-handers, and more bilaterally lateralized in SLHs (Longcamp et al., 2005; Siebner et al., 2002). As the writing hand may influence the lateralization of speech, the writing hand should be recorded in brain imaging tests as well as in all other experiments and the data should be analyzed with regard to such an influence. Brain imaging techniques can be used not only to determine hemispheric activity but also to evaluate the above discussed six classes of experimental methods.

An interesting experiment with brain imaging technique would be to determine lateralization of speech in children or illiterates. According to my knowledge of the literature, such a study has not been performed until now. If the results were to be that speech is lateralized either left-hemispheric or right-hemispheric in most illiterate individuals, the ratio of right-hemispheric speech would be of interest. This ratio could confirm or disprove either the proposed theory that brain asymmetry is determined in a random process or the genetic theories, which propose a frequency of left-handedness of approximately 10% or 12%. A discovery that speech is not lateralized in any hemisphere or bilateral in both in most children or illiterates would disprove almost every theory on handedness and lateralization. In this case the lateralization of speech would be caused probably by the writing hand and not by an innate disposition (cf. Provins, 1997).

The ratio of LHWs and RHWs (and SLHs, if such figures are available) in several different groups could indirectly indicate the frequency of shifted handedness. The frequency of LHWs in different levels of education was discussed in detail (cf. 3.3.2 *Intellectual Performance and Spatial Ability*) and the design of an experiment was suggested in order to verify whether left hand writing is more often in the upper and lower performance group of a broad and representative population of school children (cf. footnote 14).

Apart from the few above quoted studies (cf. Clark, 1957; Crow et al., 1998; Douglas et al., 1967; Sovák, 1968; M. O. Wilson & Dolan, 1931) the achievement of SLHs at school compared to the achievement of nonswitched left- and right-handers has not been analyzed directly. As switching causes disorders of speech related functions, the performance of SLHs may be significantly lower in school subjects concerned with languages (foreign and native language) and literature. Also in other subjects such as music, arts, mathematics, or physics a disadvantage may be apparent.

The distribution of intelligence or academic performance may not only differ between LHWs and RHWs. If switching handedness causes such strong disturbances of brain functions as some researchers reported (Rett et al., 1973; Sattler, 2000; Sovák, 1968), a reduced incidence of LHWs and an increased incidence of RHWs can be expected in some groups with abnormal behavior or psychological problems. This may include patients with depression of unknown etiology but without cerebral lesions or defects, individuals with speech related impairments (writing problems, stuttering, dyslexia, and dysgraphia), or prison inmates.

For left-handers an increased prevalence of mirror writing is found (Sattler, 2000; Schott & Schott, 2004). Although the specific reasons for mirror writing are unknown, a connection with right-hemispheric lateralization of speech and preferred scanning direction from right to left may exist. It should be mentioned that mirror writing with the left hand and normal writing with the right hand are completely mirror reversed activities. For SLHs mirror writing with the left hand is much easier than mirror writing for nonswitched left- and right-handed writers because this kind of mirror writing is just a laterally reversed execution of a long practiced activity. The dominant hand and dominant hemisphere is instead carrying out the task of the nondominant hand and the nondominant hemisphere. Additionally, the direction of writing is changed to the more preferred direction from right to left. These considerations suggest further research and an attempt to develop a test method that determines differences in the mirror writing ability of switched and nonswitched individuals.

# 5 Final Remarks

The aim of this thesis is to question the very obvious observation that humans are as a majority, right-handed. Whether this majority is 85% or 95% is irrelevant in this context. One point of criticism of the previous understanding of handedness is that cause was confused with consequence. The preference for the right hand in human society (especially for writing) is the cause of certain left-hemispheric lateralization of speech even in innate but switched left-handed individuals. The innate lateralization can be changed by environmental influence and by practicing right hand writing. The innate disposition is indeed changed in many SLHs. Right-handedness is induced by a social norm and not by a genetic factor, which originates a preponderance. The belief that humans are right-handed and the right hand training in writing and other activities makes humans right-handed by majority. A lot of arguments and studies, which support this claim, were presented and discussed.

Beside the development of theory, the other problematic area of previous research is testing. The validity of questionnaires seems questionable and some studies confirm this proposition. The proposed alternative approach of testing (4 *Alternative Approach of Testing Handedness*) contains examples for new test items. Some authors (Lederer, 1939; Marchant et al., 1995; Siebner et al., 2002) applied methods, which are comparable to the suggested new approach of testing. The methods are very different to the questionnaire approach and achieved results, which by no means support the idea of human right-handedness. In the face of their own methods and their own results Marchant et al. (1995) criticized the previous methods of determining handedness with clear words:

> When results conflict, the explanation often lies in methodology. Not just the niceties of exact replication, nor even flaws in the various aspects of experimental design and statistical analyses, but the most basic problems of reliability and validity may be at fault. (p. 240)

The importance of switched left-handedness and the adverse consequences of shifting the writing hand were also discussed in detail. I want to add some speculative presumptions, which at present cannot be verified with the existing results, regarding the extent of the adverse effects of switching.

Shifting left-handedness may cause a general cerebral disorganization. This could be the reason for several psychological problems like dyslexia, dysgraphia, depression, or eating disorders in unrecognized SLHs. These disorders or others like phobias and posttraumatic stress disorders may occur more often and more seriously in SLHs although shifting may not be the only cause. Such disturbances are frequent in humans, but popular belief says that left-handers are not switched anymore in Western countries. Therefore, a need to analyze a relationship between shifted handedness and psychological disorders has not been recognized by researchers but this relationship does presumably exist. A first step towards studying this concept would be to determine whether the mentioned psychological disorders occur with different frequency in LHWs and RHWs.

Shifted handedness also has a social significance. On the one hand, the reduced level of quality of life and personal well-being should be considered and on the other hand, economic implications exist. Investments in education of SLHs at school and university may be ineffective or demand higher expenditures to further the career of SLHs. The productivity of SLHs and their ability to cope with stress can be limited and their proneness to illness may be increased.

Overall, what Ballard (1911-12) recommended nearly a century ago should have been taken into account long before now: "Writing should always be done by the superior hand, and *by the superior hand exclusively*" (p. 309). I would also like to add the following: And some more effort should have been made to find out which hand is the superior one. At the same time a German author (Schaefer, 1911) also made a similar and unnoticed proposal: "Left-handers should write, draw, and do sewing and knitting with the left hand just as right-handers with the right" (p. 300).

Finally, I would like to suggest how I regard the position of this thesis in the context of handedness research. A more detailed discussion would have been desirable regarding (a) previous theories of handedness (apart from the genetic theories of McManus and Annett, which I have discussed), (b) the discussion of PLH, (c) the U-shaped distribution of handedness in monkeys and prosimians, and (d) the increased left-handedness in mentally disabled. However, due to a lack of space some details had to be left out. This concise presentation may not be an important cause to object the proposed model of handedness and someone who refuses the model is probably doing so for other reasons.

Despite the apparent notion that 85% to 95% of humans are regarded to be right-handers, I am convinced that my model of handedness is of relevance and advantage to this area of research for several reasons. First, with regard to theory, one consistent model with two main elements (innate handedness and social influence) replaces too many contradicting and partial models. Second, in terms of experiments current research suffers not from too many but from too few approaches. Current methods (questionnaires and tests) are very similar: Unimanual preference and performance is determined by means of fine motor activities. In comparison to this the proposed six item classes are very diverse. Third, a lot of research results lead to the conclusion that a considerable number of left-handers are deliberately or unintentionally switched. Only future research can indicate how many left-handers exist. Overall, I understand the previous experimental research as methodically inadequate and consider the results as contestable. On the other hand, I do not share the assumption by Kolb and Whishaw (2003), that "it is clear that we do not know why handedness occurs, and we may never know" (p. 288). The alternative handedness model explains and integrates many results of previous research, which contradict one another and do not correspond to current models and theories. Further research is absolutely necessary.[18] However, my research has shown a step in the right direction.

[18] A subsequent paper is in preparation. Results from experiments with items out of the *motor asymmetry* item class will be presented in this paper.

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