Subitizing and Visual Counting in Dyscalculia

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Abstract
The ability of recognizing the number of briefly presented items without actually counting is called subitizing (from lat. subito = suddenly). Adult subjects can subitize 3 to 4 items. For greater numbers the subjects begin a counting process relying on the visual memory of the test pattern, which needs increasingly more time as the number of items increases. For children the development of accuracy and speed of subitizing and visual counting lasts up to the adult age of 18 years.

This study tests the hypothesis that children with difficulties in acquiring basic arithmetic skills (dyscalculia) exhibit developmental deficits in subitizing and/or counting. 219 control subjects and 156 subjects with dyscalculia in the age range of 7 to 17 years were given a visual counting task, in which 1 to 9 items were presented for 100 ms. The subjects had to press a digit key on a numerical keyboard to indicate the number of items they had seen. Percentages of correct responses and response times were recorded.

The analysis shows systematic differences between control and dyscalculia children increasing with age. The percentage of dyscalculia children performing below the 16-percentile of the age matched controls was estimated between 40% and 78% increasing with age.

Introduction

The human brain has the capacity of correctly recognizing the number of items that have been presented for 100ms only. The presentation time is too short to count the items by scanning saccades. The item number is either recognized immediately without a conscious process of counting (subitizing for item numbers up to 4) or by counting the items using visual memory (Cowan, 2001); (Trick et al., 1994). The subitizing part of the process is characterized by a response time, which is about the same (or slightly increasing) for 1 to 3 or 4 items, while in the counting part linearly increasing response times are observed indicating that for each additional item a constant extra time is needed (Kaufman et al., 1949); (Piazza et al., 2002).

The question whether subitizing and counting are two separate processes in the brain is still discussed (Piazza et al., 2002); (Balakrishnan et al., 1991); (Mandler et al., 1982); (Simon et al., 1996); (Trick et al., 1994). A PET-study has shown, that both processes use the same structures of the extra striate middle occipital and intraparietal area (Piazza et al., 2002). The analysis of the response times of subitizing and counting has revealed high correlations between the speed of both processes (Fischer et al., 2005) indicating that the two components may not be completely independent.

Recently it has been shown, that subitizing and counting both undergo a long lasting development during which the speed and accuracy of subitizing and counting increases until the age of 18 years (Fischer et al., 2005). This implies that children at the beginning of school are far from the performance level of adults.

It has been speculated that the basic visual capacity of subitizing is used by the brain to develop a sense of number, which allows to associate the number words (the auditory signal) and the digits (the visual signal) with the number of items for which they stand (4). In this study we addressed this question by determining the performance on a standardized visual counting task given to control children and to children, who have specific problems in acquiring basic arithmetic skills, who for example, use their fingers to add 3 to 4 still at an age of 8 years or older.

The data show, that developmental deficits can be found by using this diagnostic task: the development is considerably slower in dyscalculia children as compared to the controls. In the companion paper it is shown that the visual capacity of subitizing and counting can be improved by daily practice and that this improvement results in a significant profit in the acquirements of basic mathematical processes.

Methods

Subjects: The 375 subjects were 7 to 17 years old. They were divided into 4 different age groups as shown in Table 1. Controls were recruited from schools in Freiburg and the vicinity. They were selected on the basis of their general performance at school and showed no indications for dyslexia, attentional deficits hyperactivity disorder, or dyscalculia as indicated by their grades. Children with dyscalculia suffered from poor performance in the basic arithmetic skills (Zareki, DMath) but reached normal reading and spelling levels. General intelligence (IQ) was measured by the Kaufmann ABC or the HAWIK test. Children with IQs below 85 were excluded from the study.

Visual stimuli and task: One to 9 small circles (items) were presented simultaneously on a small

LCD display (2,5cm x 6cm, outer borders) corresponding to 5.7 x 11.4 deg of visual angle at a viewing distance of 30cm. The circles were 2mm in size (0.04 deg) and were presented in black against a greenish background. The minimum distance between the stimuli was 8mm horizontally and 5mm vertically. The spatial positions of the items were randomized within a 4 x 4 array. Fig.1 shows examples of the presentation of 4, 6, and 8 items. By chance, some of the presentations looked like regular (like the numbers on a die) others looked completely irregular.

A central fixation mark was presented in the centre of the display. It was turned off when the stimuli were presented. Therefore, all stimuli were presented parafoveally. The stimuli were presented for 100ms (the shortest saccadic reaction time) to prevent any saccade that the subjects could possibly make to count the stimuli by scanning saccades. A longer but limited exposure time would confound enumeration by saccades with subitizing (Jensen et al., 1950). The limited presentation time did not imply a limited time to find the response (see below).

The visual display, the keyboard, and data collection were all implemented in a small hand held instrument.

Procedure: The subjects were introduced to the task by presenting each set of items for an unlimited period of time. They were instructed to press a key corresponding to the number of items at the display. The spatial arrangement of the digit keys was identical to those of the numerical keyboards of computers. At least 12 practice trials of this kind were given. Subjects were informed that reaction time was important. Therefore they were also instructed to place their hand just above the keyboard. After they understood the task all subjects were given another 5 trials of the real task for practice, i.e. presentation time was only 100 ms. The central fixation point was presented first. After 1 sec the fixation point disappeared, the test pattern was presented, and the subject responded by pressing the response key. The next trial was initiated only after another key press by the subject. Each number of items was shown 20 times with the exception of a single item, which occurred only 10 times. Altogether, 170 trials were run for each subject. The total time for a test session was about 20 min.

Data collection and analysis: The data were recorded by the test instrument and downloaded to a PC for later analysis. For each subject and each trial the number of items (N) presented and the number (n) given as the response were recorded. The response time r between the end of the presentation to the key press was also recorded.

For each subject and for each number of items we calculated the percentage of correct responses p(N) and the corresponding mean response time r(N). In a next step of analysis we calculated the linear regression between the response times and the item number for N=4 to N =8. For N > 3 an almost linear relationship was obtained for most subjects. The basic reaction time T was calculated as the mean value of r(1). The mean percentage of the correct responses was calculated for item numbers between 4 and 8. Item number 9 was excluded from this analysis, since most children noticed that 9 was the highest number on the key board and pressed 9, whenever the item number was "large". They hit the correct key often by guessing (Sathian et al., 1999). We also calculated these values separately for regular and irregular patterns and found slight differences only for item numbers above 5. These slight profits were similar in both groups and therefore neglected in the final analysis.

To compare the performance of the control and the dyscalculia subjects age curves of the characteristic variables were calculated. The characteristic variables were: the basic response time T; the time per item t, averaged for item numbers 4 to 8; the correctness P is the mean value of the percentages of correct responses averaged over item numbers 4 to 8. We also calculated the effective recognition speed by dividing P by t. ANOVAs were used to determine the significance of the differences between groups.

Results

Count curves: The typical form of count curves of a group of controls aged 11-13 years can be seen in Fig.2. High percentages of correct responses were obtained for item numbers below 4. For larger item numbers a clear decline can be seen. For 8 items about 65% of the responses were still correct. Children with dyscalculia showed a qualitatively similar behaviour, but the curves show smaller values of correct responses. Note that even for small item numbers of 1 to 3 about 5% errors were made by the dyscalculia subjects. With increasing item number the differences between the curves increased.

Response times as a function of item number are shown in Fig.3 for the same age groups as in Fig.2. Again the curves have similar forms, but the curves for dyscalculia children were displaced vertically to longer response times. Note that even for small item numbers 1 and 2 the dyscalculia children were slower than the control children. With increasing item number the response times became longer in an almost linear fashion indicating that both groups needed a constant additional time for each additional item given by the slopes t of the linear parts of the curves.

Age curves: Count curves (as shown in Fig.2 and 3 for age group 3) were obtained for all age groups. To examine at the age effects characteristic variables were calculated for each curve. The basic response time T was calculated as the mean response time for a single item. The time per item t was calculated as the mean slope of the linear (counting) part using the response times for item numbers 4 to 8 (see regression line in Fig.3). The correctness of the counting responses was characterized by the mean value P for item numbers 4 to 8.

Fig.4 shows the age curves of the basic response T for both groups. The developmental decrease can be seen in both groups, but the dyscalculia subjects showed a systematically slower development. While the differences were close to nothing for the youngest age group they were highly significant for the age groups 2 and 3. Age group 4 contained only 9 dyscalculia subjects with a large inter-individual scatter. The difference between control and dyscalculia subjects in this age group did not reach significance. The resulted in F=60.15 (p=0.0001) and with age as covariate we obtained F=25.8 (p=0.0001). The linear correlation coefficient was r = - 0.616.

Fig.5 shows the age curves for correctness P and the time per item t describing the counting part of the process. The discrepancy in both pairs of curves shows that the dyscalculia subjects reached lower correctness with lower speed than the controls.They could not use the longer response times to reach as many correct results as the control children. On the contrary, they took more time for each additional item and made more mistakes than the controls. The ANOVA for the variable P resulted in F=77.51 (p=0.0001) and with age as covariate F=48.22 (p=0.0001). The correlation coefficient was r=0.342. ANOVA results for the variable t were F=79.1 (p= 0.0001) and with age as covariate F=38.03 (p=0.0001), and r = -0.513.

Percentage of off-limit subjects: In practice it is of interest to know how many subjects from a test group failed to reach the criterion of a control group. For an estimate we used the effective recognition defined by P/t, which combines the correctness and the time per item calculated for item numbers 4 to 8. Fig.6 shows the two age curves. The numbers indicate the percentages of dyscalculia subjects performing below the 16-percentile of the controls.

The figure shows that these percentages among the dyscalculia subjects increase with increasing age. While in the youngest group about 40% of the dyscalculia subjects failed to reach the limit, for age group 3 children this percentage increased to about 78%.

Differences due to gender were not significant when comparing the effective recognition values.

The further analysis shows that the use of small item numbers also differentiated between the groups. We used the average values of P/t averaged for item numbers 2, 3 and 4 to calculate the effective recognition speed of subitizing. We obtained clear developmental deficits increasing with age in a very similar way as the variable shown in Fig.6.

In other words: even when dealing with small item numbers dyscalculia children performed below the level of the controls at any age tested in this study.

Discussion

The present study shows that the capacity of counting one up to eight briefly presented items is lower for children with problems in acquiring basic arithmetic skills. The deficits occur in all age groups and increase with age. The responses of the dyscalculia subjects were slower and more often incorrect even for item numbers below 3 or 4. In dyscalculia the special visual capacity of subitizing and counting suffers from developmental deficits in 40 to 80% of the cases.

A study by B. Fussenegger (Austria) examined also children (2. and 3. grade) with dyscalculia with respect to subitizing and counting (dot estimation). In comparison with age matched controls she found significant differences referring to the accuracy of the task performance (personal communication, Dissertation at the University of Innsbruck, Austria).

From PET-studies it is known that the extrastriate middle occipital and the parietal cortical areas are involved in subitizing and counting (Piazza et al., 2002). Since the stimuli in the present study were presented only briefly, it was impossible to count the items by scanning them by saccades. The items were seen by parafoveal vision and were obviously stored in memory. The subitizing and/or counting process relied on the effectiveness of storing and reading the data. A deficit in this function may indeed contribute to the problems of dyscalculia subjects, because they could not use this visual memory function as effectively as other children when they were supposed to develop a sense of number: the inner representation of "how many items" there are and which is meant by the number word "five" and/or by the digit "5" was not immediately available for them.

At this point the idea of a causal relationship between dyscalculia and subitizing must still be considered as an hypothesis. However, similar to other sensory and optomotor functions subitizing and counting may be improved by specific training procedures. Whether a successful training results in a profit in acquiring basic arithmetic skills will be considered in the following paper.

It might be interesting to compare the present results with those of dyslexic subjects, who were diagnosed for deficits in saccade control and low level auditory discrimination. First of all the temporal extend of the development is very similar lasting also until adulthood (Fischer et al., 1997); (Fischer et al., 2001). Second, dyslexics exhibit deficits in one or both of the optomotor (Biscaldi et al., 2000) and auditory domains (Fischer et al., 2004). Specific daily practice of saccade control and/or low level auditory functions reduces the developmental deficits in up to 70 to 85% of cases (Fischer et al., 2000); (Schäffler et al., 2004) and leads to profits in the process of acquiring reading and spelling skills (Schäffler et al., 2004). Preliminary data from our laboratory show, that up to 60% of dyslexic children also suffer often from deficits in subitizing and counting and dyscalculia children may also suffer from deficits in saccade control.

References

Balakrishnan JD and Ashby FG. 1991. Is subitizing a unique numerical ability? *Percept Psychophys* **50:** 555-564.

Biscaldi M, Fischer B, and Hartnegg K. 2000. Voluntary saccade control in dyslexia. *Perception* **29:** 509-521.

Cowan N. 2001. The magical numbr 4 in short-term memory: A reconsideration of mental storage capacity. *Behav Brain Sci* **26:** 87-116.

Dehaene.Der Zahlensinn. Basel: Birkhäuser Verlag; 1999.

Fischer B, Biscaldi M, and Gezeck S. 1997. On the development of voluntary and reflexive components in human saccade generation. *Brain-Res* **754:** 285-297.

Fischer B, Gebhardt C, and Hartnegg K. 2005. Age effects in subitizing and visual counting. *PERCEPTION submitted*

Fischer B and Hartnegg K. 2000. Effects of visual training on saccade control in dyslexia. *Perception* **29:** 531-542.

Fischer B and Hartnegg K. 2001. On the development of low level auditory discrimination. *www dyslexia-journal com*

Fischer B and Hartnegg K. 2004. On the development of low level auditory discrimination and deficits in dyslexia. *Dyslexia* **10:** 105-118

Jensen EM, Reese EP, and Reese TW. 1950. The subitizing and counting of visually presented fields of dots. *Journal of Psychology: Interdisciplinary & Applied* **30:** 363-392.

Kaufman EL, Lord MW, Reese T, and Volkman J. 1949. The discrimination of visual number. *Am J Psychol* **62:** 498-525.

Mandler G and Shebo BJ. 1982. Subitizing: An analysis of its component processes. *J Exp Psychol Gen* **11:** 1-22.

Piazza M, Mechelli A, Butterworth B, and Price CJ. 2002. Are subitizing and counting implemented as separate or functionally overlapping pocesses? *Neuroimage* **15:** 435-446.

Sathian K, Simon TJ, Peterson S, Patel GA, Hoffman JM, and Grafton ST. 1999. Neural evidence linking visual object enumeration and attention. *J Cogn Neurosci* **11:** 36-51.

Schäffler T, Sonntag J, and Fischer B. 2004. The effect of daily practice on low level auditory discrimination, phonological skills, and spelling in dyslexia. *Dyslexia* **10:** 119-130.

Simon T and Vaishsnavi S. 1996. Subitizing and counting depend on different attentional mechnisms: Evidence from visual enumeration in afterimages. *Percept Psychophys* **58:** 915-926.

Trick LM and Phylyshyn ZW. 1994. Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychol Rev* **101:** 80-102.

Captions

Table1 The table shows the number of female and male subjects in both groups being divided into 4 age groups. Mean age and standard deviations are given. Altogether 375 (207f/168m) participated in this study

Fig.1 Typical examples of presentations of 4, 6, and 8 items

Fig.2 Percentages of correct responses as a function of item number. The vertical bars indicate confidence intervals

Fig.3 Mean response times as a function of item number. The linear regression (dotted) line has the slope t (defining the time per item). The vertical bars indicate confidence intervals

Fig.4 The decrease of the basic response time T is shown as a function of age for both groups of subjects

Fig.5 The percentage of correct responses (left) and the time per item (right) are shown as a function of age for both groups of subjects

Fig.6 The effective recognition as a function of age for both groups of subjects. The numbers indicate the percentage of dyscalculia subjects performing below the 16-percentile of the controls

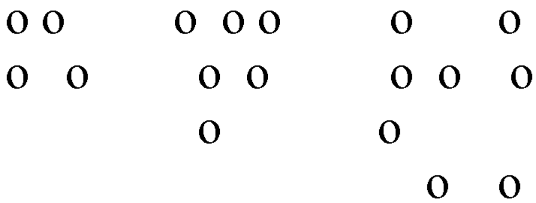

Fig.1 Methods

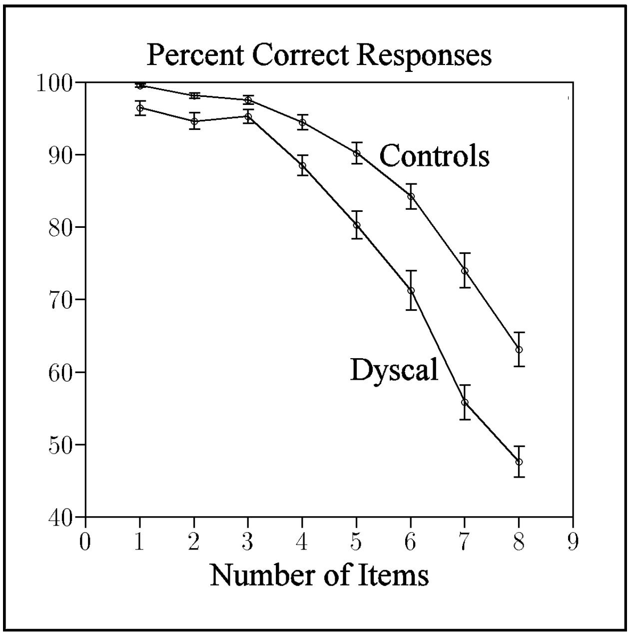
Percent Correct Responses
100
90
80
70
60
50
40
0
1
2
3
4
5
6
7
8
9
Controls
Dyscal
Number of Items

Fig.2　pr-n3-kd

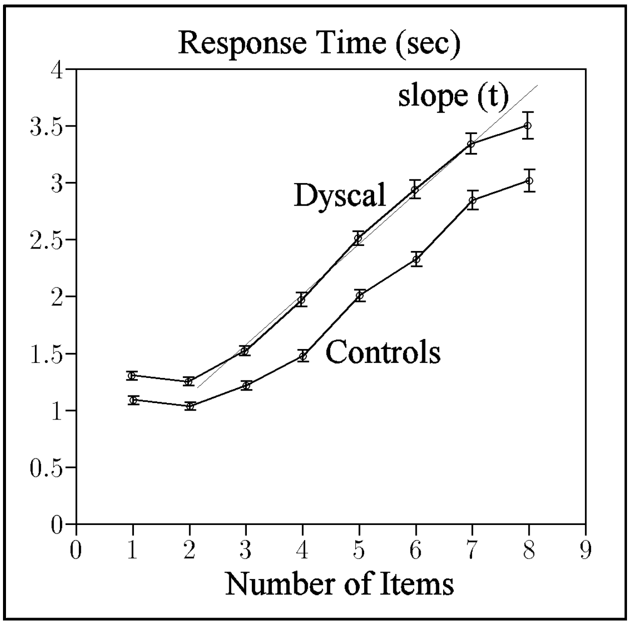
Response Time (sec)
slope (t)
Dyscal
Controls
Number of Items
0 0.5 1 1.5 2 2.5 3 3.5 4
0 1 2 3 4 5 6 7 8 9

Fig.3 tr-n3-kd

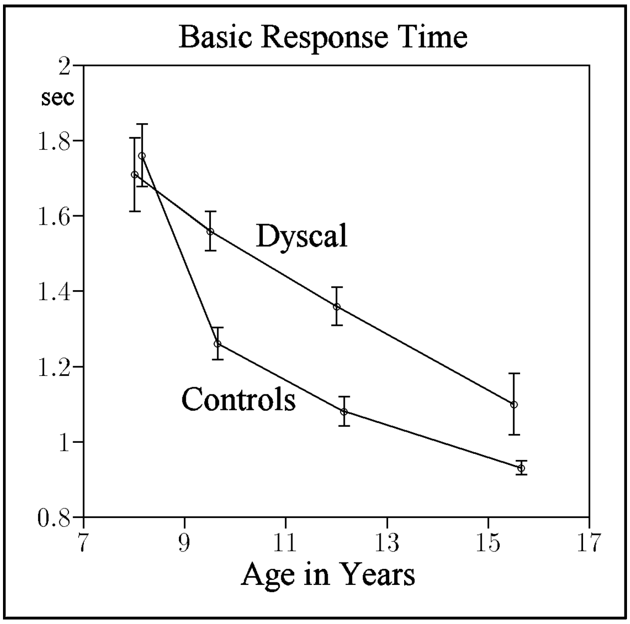
Basic Response Time
2
sec
1.8
1.6
1.4
1.2
1
0.8
7
9
11
13
15
17
Dyscal
Controls
Age in Years

Fig.4 t1-kd

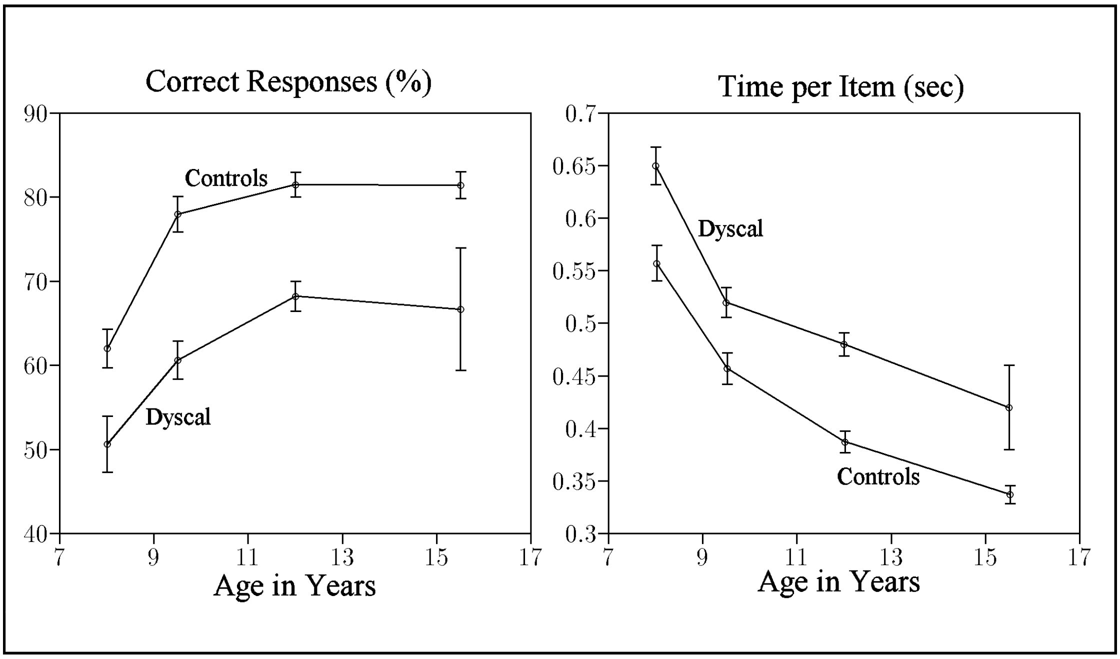

Fig.5 prgtr-kd

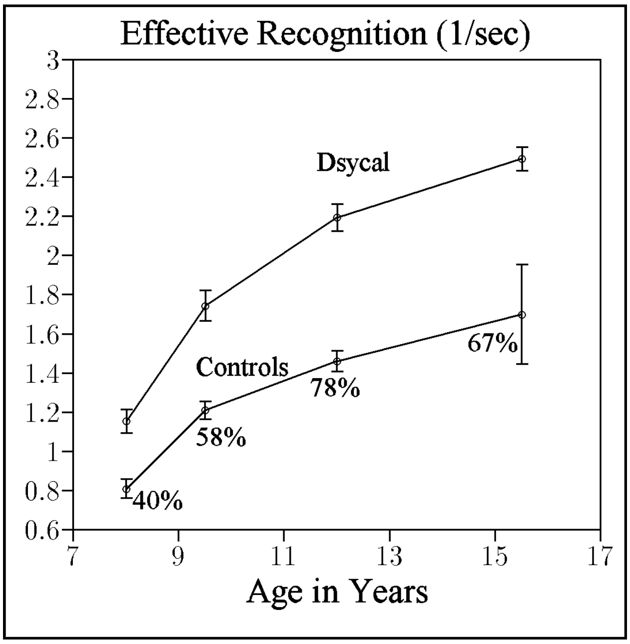

Fig.6 eeg-kd.pcx

	7-8 years	9-10 years	11-13 years	14-17 years	all
Controls					
Number	35 (18f/17m)	36 (20f/16m)	62 (36f/26m)	86 (54f/32m)	219 (128f/91m)
mean age (y)	7,5 ± 0,5	9,6 ± 0,5	11,9 ± 0,8	15,4 ± 1,0	
Dyscal					
Number	20 (14f/6m)	60 (32f/28m)	67 (32f/35m)	9 (1f/8m)	156 (79f/77m)
mean age (y)	7,6 ± 0,5	9,6 ± 0,5	11,7 ± 0,8	15,6 ± 1,2	

Table 1