Review Article

Functional and structural neural plasticity effects of literacy acquisition in adulthood

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Abstract: In Germany, 7.5 Million individuals between 18 and 64 years are considered to be functionally illiterate (Grotlüschen & Riekmann, 2012). Functional illiterates have only rudimentary literacy skills despite attending school for several years. Although they can use written language to a very limited extent, only few functional illiterates attend literacy courses for adults. In addition, most adult literacy courses primarily aim at promoting basic reading and writing skills. Offers specific to workplace literacy are scarce.

This review gives an overview of the definition of functional illiteracy. Afterwards, a specific literacy program (AlphaPlus) and its effectiveness will be presented. The reviewed studies indicate that learning to read in adulthood is associated with structural and functional brain changes.

Keywords: functional illiteracy, reading, writing, training, fMRI

Funktionelle und strukturelle neuronale Plastizitätseffekte beim Erwerb von Alphabetisierung bei Erwachsenen

Zusammenfassung: 7.5 Millionen Erwachsene in Deutschland haben große Probleme die schriftsprachlichen Anforderungen, die an sie im Alltag gestellt werden, zu erfüllen. Sie werden als funktionale Analpabeten bezeichnet. In dieser Überblicksarbeit wird das Trainingsprogramm AlphaPlus vorgestellt, das speziell für die Verbesserung der Schriftsprachkompetenz von Erwachsenen konzipiert wurde. Der Schwerpunkt dieses modularen Programms liegt auf der Vermittlung arbeitplatz-relevanter schriftsprachlicher Fähigkeiten. Es werden vier Studien vorgestellt, die die Verbesserungen der Lese- und Schreibfähigkeit durch das Training belegen und die neuroplatischen Veränderungen, die beim Leseerwerb im Erwachsenenalter auftreten, charakterisieren.

Keywords: funktionaler Analpabetismus, Lesen, Schreiben, Training, fMRT

In countries with compulsory schooling and a well-developed educational system, adults are generally expected to master the most basic educational skills. However, it has been known since the late 1970s that in Germany, as in other industrialized countries, many adults are only barely literate. Affected individuals are referred to as "functional illiterates", since their literacy skills are not sufficient to cope with language-related demands of their environment without help. Literacy skills are important in all areas of life where written language is used for communication and information gathering. The higher the social requirements for the written language, the more serious are the consequences for functional illiterates (Döbert & Hubertus, 2000).

Magnitude of Functional Illiteracy in Germany

A recent survey (LEO) concludes that there are about 7.5 Million functional illiterates in Germany (14.5 % of the adult population (Grotlüschen & Riekmann, 2012)). Similar prevalence rates are reported for other industrialized countries, e.g. 9 % for France (ANLCI, 2007) or 16 % for the United Kingdom (Williams, Clemens, Oleinikova & Tarvin, 2003).

For the LEO survey (Grotlüschen & Riekmann, 2012), the lowest level of competence in written literacy was subdivided into six parts, the so-called "alpha-levels". The alpha-levels one to three refer to functional illiteracy: al-

https://doi.org/10.1024/1016-264X/a000xxx

pha-level one and two describe illiteracy in the strictest sense. Affected individuals (2.3 Million) have the most serious impairment, as they can only read and write simple words. Individuals at alpha-level three (5.2 Million) can read words as well as short sentences, but have difficulties reading coherent texts. Alpha-level four (13.3 Million) is characterized by incorrect writing. Individuals at alpha-levels five and six read complex texts and write words orthographically correctly.

Neurobiological causes of functional illiteracy

For developmental dyslexia, there is a broad scientific consensus that there is a deficit in phonological information processing at the cognitive level. Neurobiologically, the phonological deficits are attributed to congenital dysfunction of central speech regions of the left hemisphere. This is supported by anatomical, structural and functional abnormalities that have been proven in a large number of studies (for comprehensive reviews, see Ozernov-Palchik et al., 2018; Richlan, Kronbichler & Wimmer, 2009, 2013). Several genes linked to dyslexia are associated with neuroanatomical changes (Gialluisi et al., 2019). Similar to developmental literacy disorders (Gaab et al., 2007; Raschle, Stering, Meissner & Gaab, 2014), functional illiteracy is also associated with phonological deficits (Greenberg & Ehri, 2002; Greenberg & Lackey, 2006). In addition to phonological deficits, some authors consider a deficit of basic perceptive abilities as a possible cause for difficulties in literacy acquisition (Tallal, Miller & Fitch, 1993). According to these authors, fundamental perceptual deficits result in problems to discriminate stimuli, whose identification requires a fine temporal resolution. The distinction of many phonemes (e.g., /ba/, /pa/, /ka/, /ga/, /ta/, /da/) requires such fine temporal discrimination. Individuals with normal perceptual abilities have stable representations of these phonemes. This enables them to discriminate phonemes in spoken and written language without effort. However, if the basic perceptual functions are impaired, stable representations of these phonemes cannot be stored in memory. When affected children learn to read, the weak phoneme representations lead to difficulties in learning the grapheme-phoneme conversion (i.e., assignment of letters to sound units of speech). Tallal and colleagues refer to this approach as "rapid auditory processing deficit hypothesis". Deficits in auditory processing have been demonstrated for a subgroup of individuals with developmental dyslexia (Bishop, 2007; Hämäläinen, Salminen & Leppänen, 2013; Ramus et al., 2003; Rosen, 2003; Volkmer & Schulte-Körne, 2018) and functional illiterates (Rüsseler, Gerth & Boltzmann, 2011; Schaadt, Pannekamp & van der Meer, 2013). However, despite these positive findings, it does not necessarily imply a causal relationship between auditory deficits and the emergence of literacy problems. Due to the observed similarities, functional illiteracy is considered by some authors to be a manifestation of developmental dyslexia that has not been adequately treated in childhood (Greenberg et al., 1997).

Basic Education and Literacy Programs

Surveys such as PISA (Baumert et al., 2001), PIAAC (Rammstedt, 2013) and LEO (Grotlüschen & Riekmann, 2012) suggest that the German educational system fails to provide adequate basic literacy skills to the entire population. For this reason, further educational programs must be made available, where adults can acquire missing competencies after the end of regular schooling. Every year around 11.000 to 12.000 adults are taught at adult education centers (Frieling & Rustemeyer, 2011). These courses are aimed primarily at native German speakers. For individuals with a migration background, there are specific integration courses funded by the Federal Office for Migration and Refugees (BAMF) (Rosenbladt & Bilger, 2013).

Overall, conventional literacy programs are only attended by a small proportion of functional illiterates. The reasons for this are manifold and range from the poor accessibility of existing offers to the lack of motivation of the individual to overcome the existing deficits. Despite these non-negligible barriers, some of those affected still choose to attend literacy courses to overcome their difficulties. Often, critical life events such as the death of a close relative, the separation from the spouse, the schooling of children or promotion prospects trigger the decision (Egloff, 2007). Importantly, participants of literacy courses are not to be equated with the group of 7.5 Million functional illiterates described in the LEO survey. Their social profile is more similar to those of the two million adults referred to as "illiterate in the narrow sense" (i.e. alpha-levels 1 and 2). An essential difference is that the majority of participants of adult education programs do not have a school degree. However, according to the results of the Leo study, many functional illiterates have completed secondary education or higher. As people with a school degree are generally expected to master written language, the social barrier to participate in literacy courses is relatively high for this subgroup (Rosenbladt, 2012). This finding underlines the strong selectivity in access to the courses.

Work-oriented Basic Education

Since a significant proportion of functional illiterates are gainfully employed, companies should also be considered as learning venues where work-oriented literacy and basic education is provided. According to the LEO survey, about 57 percent of functionally illiterate adults are employed (Grotlüschen & Riekmann, 2012). However, the extent of their deficits largely determines their occupations. The lower their skills, the more likely they are to work as unskilled or semi-skilled workers. At alpha-level three and above, persons have greater chances to be employed compared to alpha-level one or two. As in illiterates "in the narrower sense" literacy deficits are particularly pronounced, they are more affected by unemployment.

Several advances, such as the automation of processes in production or the development of new technologies, are constantly changing existing work processes and increasing the demands on the qualifications of employees. Even in the area of simple manual tasks, which often did not require vocational training, the complexity of work processes and work demands increases. Workers must be able to understand information about changes in work and production processes and to inform colleagues. In many areas, there is an increased need for documentation, often in written, digital form. As a result, there is an increased need, especially for older workers, to learn how to deal with new media. Without vocational training, it will become increasingly difficult to meet these requirements (Klein & Schöppe-Grabe, 2011). Nevertheless, the number of unskilled and semi-skilled workers is surprisingly high: 7.3 Million of all employees have no completed vocational training. One third of them also do not have a school degree. For most companies, the inadequate basic education of their low-skilled employees plays a subordinate role. Although more than 80 percent of companies provide in-company training (Klein & Schöppe-Grabe, 2011), it is more about work-related skills than basic education aspects such as reading, writing or arithmetic. This is partly due to the fact that many companies are unaware that they have low-skilled workers belonging to the group of functional illiterates. However, given the threatening lack of qualified employees, there is a great need for literacy and basic education programs that specifically target employed functional illiterates.

In addition, literacy programs for unemployed functional illiterates should be provided, in order to increase their chances of returning to work. Trainees should also be considered in the context of qualification programs. The PISA surveys have shown that a significant proportion of 15-year-olds at the end of lower secondary education do not meet the requirements for successfully completing vocational training. Their lack of basic literacy skills jeopardizes their chances of finding an apprenticeship or a job, as in most occupations basic literacy skills are required.

Altogether, it can be concluded that work-related literacy and basic education should target the low-skilled individuals who are 1) employed, 2) unemployed and 3) in occupational training. AlphaPlus is a special literacy and basic education program targeting these three groups. This new approach was developed as part of a joint project funded by the German Federal Ministry of Education and Research.

AlphaPlus as an Example of a Work-oriented Basic Education Program

AlphaPlus is a program developed for adults with literacy skills at alpha-level 1 to 3. The program can be used both in job-related basic education of employees and in currently unemployed individuals. In addition, the program is also suitable for promoting literacy skills of young adults at the very beginning of their professional careers.

The program is aimed at both native German speakers and persons with a migration background. However, a prerequisite for persons with a migration background is that they have basic German language skills that enable them to understand and implement instructions. It should also be noted that individuals from other cultures have to be distinguished with regard to whether they are literalized in their mother tongue or not. The concrete structure of the program depends strongly on whether the mastery of a written language has already been acquired for another language.

AlphaPlus consists of seven modules, which together form the basis for an independent basic education program. The program is designed for a duration of nine months and can be carried out both part-time and full-time. In the part-time version, lessons take place before, during or after working hours either at the workplace or in an educational institution. In the full-time version, which aims at individuals without current employment, lessons are offered daily from Monday to Friday. It is also possible to integrate single modules in other, already existing basic education concepts or to use specific components separately. The individual modules are briefly described below. For more detailed information see Boltzmann et al. (2015).

Module 1: Classical Literacy Lessons

The classical literacy lessons have a modular structure. There are four different modules of increasing complexity, which can be used flexibly in the classroom. For each module, there is a textbook that contains specific tasks (https://

www.bnw.de/bnwde/content/deutsch/unternehmen/qualifizierung/grundbildung). Whether and to what extent the modules are taught depends on the respective previous knowledge of the participants, their learning development and motivation.

Module 2: Audio-Trainer

Basic perceptional functions in the visual, auditory and motor area can be trained with the Audio-Trainer. The Audio-Trainer is available as an independent device but is also implemented in the Alpha Trainer (see Module 3). The repeated practice of the eight tasks leads to an automation of the trained skills and facilitates the acquisition of written language via transfer effects (Warnke, 2006). The perceptual abilities are trained intensively at the beginning of the program; later, only refresher sessions take place.

Module 3: Alpha-Trainer

With the help of the Alpha Trainer, language and perceptual functions are promoted through "lateralized synchronous speech". In lateralized synchronous speech, the trainee vocalizes individual syllables, words, sentences or texts in sync with a model voice. The two different language information (model voice and own voice) are constantly moving in opposite directions from the left to the right ear and back again. In this way, the two voices can be perceived separately and compared with each other. In addition, the training elements are presented not only acoustically but also visually. This supports the interaction and coordination of the brain hemispheres as well as the integration of visual and auditory input.

The idea of lateral training is based on scientific research, suggesting that the corpus callosum is smaller and functionally impaired in individuals with literacy problems (Fine, Semrud-Clikeman, Keith, Stapleton & Hynd, 2007). The corpus callosum has been implicated, among other things, in motor functions, sensory integration processes and the exchange of information between the hemispheres (Petersson, Ingvar & Reis, 2009). The exchange of information between the left and right hemispheres during lateral training aims to improve the coordination, synchronization and connectivity of the brain hemispheres.

Module 4: Sound Discrimination Training

With the sound discrimination trainer, the distinction between consonants and vowels is practiced. The trainee hears short words presented alternately to the left and right ear. Each stimulus begins and ends with a vowel; the middle letter is an alternating consonant (e.g., "efi", "eki") or a letter combination (e.g., "ch", "sch"). By pressing a button, the trainee specifies the perceived middle sound. The actual number and the percentage of correctly recognized words are registered separately for the left and the right ear.

Module 5: Spelling training with Orthofix®

Orthofix® is a program for systematically learning visual images of words using the visual spelling method. On a computer screen, a word is presented, which is either spelled out or read by a model voice. The word disappears after a few seconds and the trainee is prompted to rewrite the word with the keyboard. In simple training mode, word typing is only practiced forward. In the advanced mode, the displayed words have to be typed forward and backward. In its basic form, Orthofix® contains about 10.000 of the most common German words, sorted by topic. In addition, there are job-specific word lists that allow the parallel learning of job-specific terminology. Currently, job-relevant words are implemented for 15 different occupational groups (e.g., professional care, roofers, butchers, landscaping, scaffolders). It is also possible to create own word lists.

Module 6: Online Learning Platform (www.ich-will-lernen.de)

Another component is the online learning platform "www.ich-will-lernen.de" of the German Adult Education Association. This is Germany's largest literacy learning platform with more than 31.000 exercises. It was specially developed for low-skilled adults and offers them individual learning opportunities that can be used free of charge and anonymously. In the area of "literacy and basic education" reading, writing and arithmetic can be trained. In addition, there are exercises for everyday life and basic economic education (Schön, 2014).

Module 7: Social Training

Social training provides a variety of health-promoting, social and cultural activities. These are for example: fitness training, joint cooking, communication training, participation in cultural events, preparation of application documents and support in job search.

The devices used in blocks 2 to 5 were originally developed by MediTECH Electronic GmbH (www.meditech.de) for children with developmental dyslexia and adapted for adult education in AlphaPlus. At the beginning of the training, the participants get an introduction to the mechanisms of the devices. This ensures that they understand and internalize the relationship between technology-based learning and improvements in literacy skills.

Literacy Acquisition in Adulthood

We examined whether participation in a specific adult literacy program (AlphaPlus) results in improved literacy skills and how these improvements are associated with neuronal changes.

Changes in reading and writing performance

The reading ability of functionally illiterate adults was assessed with the WLLP (Würzburger Leise-Leseprobe; Küspert & Schneider, 1998). In this test, 140 written words as well as four pictures next to each word are presented. Participants have to mark the one picture that represents the word on the left side. The test score comprises the number of correctly identified pictures in five minutes. The WLLP is supposed to measure silent reading speed and the ability to decode written words. To assess the writing ability of functional illiterates, a standardized German test for the first grade was used (Diagnostischer Rechtschreibtest (DRT 1), Müller, 2004). Here, participants have to write 32 single words from dictation. We used parallel versions of the WLLP and DRT1 at the beginning and at the end of the AlphaPlus program in order to examine whether the reading and writing abilities had changed over time.

Table 1 presents descriptive characteristics of each group for the variables sex, age, handedness and non-verbal IQ.

To specifically evaluate the effectiveness of the AlphaPlus program, training-related changes in literacy skills were compared between functional illiterate adults taking part in different literacy trainings differing mainly in the intensity of the delivered training. The experimental group participated in a high-intensity training (AlphaPlus group) and the control group participated in a low-intensity training. Reading and writing abilities of both functionally illiterate groups before and after the training were analyzed using a two-way, repeated measures ANOVA with two levels of SESSION (pretest vs. posttest) and two levels of GROUP (AlphaPlus vs. Control).

For *reading ability*, the ANOVA revealed a significant main effect of SESSION ($F(1,45) = 18.83$, $p < .001$) and a significant interaction of SESSION by GROUP ($F(1,45) = 7.39$, $p < .01$). According to post-hoc paired *T tests*, only the AlphaPlus group improved in their reading ability from pre- to posttest ($T(35) = -6.72$, $p < .001$), while participants of the control group did not show any considerable changes in their reading scores (Figure 1-A). Although the increase of an average of 19 words in the AlphaPlus group was statistically significant, there were large differences in learning: while some participants profited greatly from participating in the AlphaPlus program, other participants showed only minor changes in their performance (the learning variation varied between 3 and 79 words). An important reason for the huge variability might be the different initial abilities of the participants, i.e. between 2 and 101 words were correctly identified at the beginning of the course (compared to elementary school children, the average abilities of the participants corresponded to those of first-grade students). Nevertheless, the average performance of the AlphaPlus group has improved overall to the level of a second-grade student.

For writing ability, a significant main effect of SESSION ($F(1,45) = 6.84$, $p < .05$) and a significant interaction of SESSION by GROUP was found ($F(1,45) = 19.81$; $p < .001$). This effect is mainly due to the fact that participants of the AlphaPlus program significantly reduced the number of errors in the DRT ($T(35) = 6.61$, $p < .001$), while there were no statistically reliable changes in the control group (Figure 1-B).

Table 1. Characteristics of participants.

		Functional illiterates	
		AlphaPlus (*n* = 36)	Controls (*n* = 10)
Sex		26 male	7 male
Age		42.50 ± 8.43	41.82 ± 10.71
WLLP	T1	45.08 ± 29.66	54.00 ± 18.78
(correct items)	T2	64.08 ± 35.05	58.36 ± 19.37
DRT	T1	15.17 ± 10.04	7.82 ± 6.63
(errors)	T2	9.92 ± 8.44	9.18 ± 6.21

Modulation of Early Visual Word Recognition

Visual stimuli evoke a negative-going event-related potential peaking between 120 ms and 200 ms after stimulus onset, which is often referred to as N170. Although this component is triggered by any visual stimulus, the amplitude strongly depends on the perceptual familiarity of certain stimulus classes. The word-related N170 is an ERP component which reflects fast recognition of visually presented words and develops within the first years of reading acquisition (Maurer et al., 2006; Maurer et al., 2011). The source of the word-related N170 is supposed to coincide with a particular area located in the mid-portion of the left fusiform gyrus (Bentin, Allison, Puce, Perez & McCarthy, 1996; Yoncheva, Blau, Maurer & McCandliss, 2010), the putative visual word form area (VWFA, (Cohen et al., 2000; Dehaene, Le Clec'H, Poline, Le Bihan & Cohen, 2002)).

We investigated with an implicit reading task whether the N170 can still be modulated when adults learn to read fluently (Boltzmann & Rüsseler, 2013). During the EEG recording, simple words (e.g., house) and symbols (e.g., ○◇□○) were presented. As a main result, functionally illiterate adults showed a distinct N170 for word-like stimuli and symbols, which resembled the clear N170-differ-

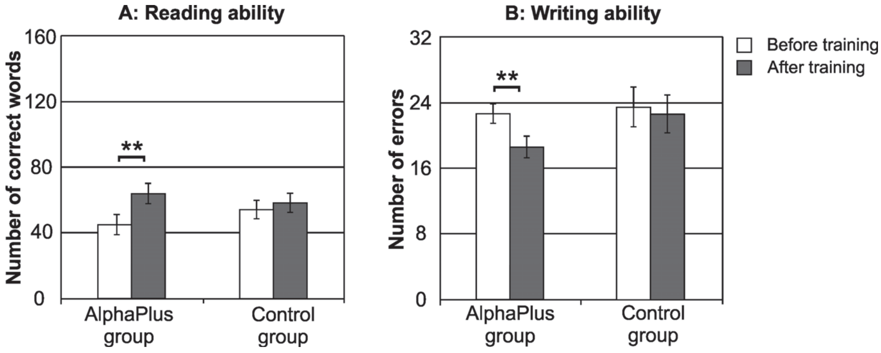

Figure 1. Reading (A) and writing (B) performance of functional illiterates participating in a high-intensity training (AlphaPlus group) and a low-intensity training (Control group).

ence of normal reading adults. Additionally, the N170 amplitudes were left-lateralized, which is in line with previous studies (Bentin, Mouchetant-Rostaing, Giard, Echallier & Pernier, 1999; Brem et al., 2005; Maurer, Brem, Bucher & Brandeis, 2005). Accordingly, the literacy skills of functional illiterates obtained in childhood seem to be sufficient to account for the left-lateralized discrimination between words and symbol strings. The amplitude of the word-related N170, however, increased in functional illiterates after several months of intensive literacy training (see Fig.2). The study therefore demonstrates that the N170 can still be modulated in adulthood, when functionally illiterate adults learn to read fluently.

Modulation of Structural and Functional Brain Functions

Reading depends on the functional integrity of a distributed network of different brain regions. Three systems have been identified to support the reading process (Grigorenko, 2001): A frontal system (inferior frontal gyrus), a temporo-parietal system (angular and supramarginal gyri, posterior part of the superior temporal gyrus), and an occipito-temporal system (occipito-temporal area and posterior parts of the middle and inferior temporal gyri). Children strongly rely on the frontal and temporo-parietal circuits during reading, which are involved in phonological processing. Most adults have developed such fluency and automaticity in word reading that slow and effortful phonologically processes are no longer necessary. They rather use the occipito-temporal circuit which is associated with fast and automatized processing of words.
Although only few studies investigated neuronal reading processes in functional illiterates, there is a bulk of studies dealing with developmental dyslexia. Importantly, children and adults with developmental dyslexia differ in the involvement of the neural circuits in reading-related tasks from normal readers.

Structural Changes

In contrast to normal readers, dyslexics show increased activity in the inferior frontal cortex and reduced activity in the temporo-parietal and occipito-temporal cortex of the left hemisphere (Schlaggar & McCandliss, 2007; Richlan et al., 2009; Wandell, Rauschecker & Yeatman, 2012). Due to the observed functional abnormalities in the anterior and posterior language regions, it has been hypothesized that the reading difficulties might be the consequence of a disconnection between temporo-parietal and frontal regions (Horwitz, Rumsey & Donohue, 1998; Paulesu et al., 1996; Peterson & Pennington, 2012; Temple, 2002). To test this hypothesis, researchers have studied white matter tracts in developmental dyslexia using diffusion tensor imaging (DTI). DTI is a non-invasive neuroimaging method measuring the diffusion of water molecules in brain tissue (Basser, Mattiello & LeBihan, 1994; Jones & Leemans, 2010; LeBihan et al., 2001). DTI studies in dyslexic children and adults have shown alterations of white matter in left temporo-parietal regions (Beaulieu et al., 2005; Deutsch et al., 2005; Klingberg et al., 2000) and inferior frontal regions (Carter et al., 2009; Rimrodt, Peterson,

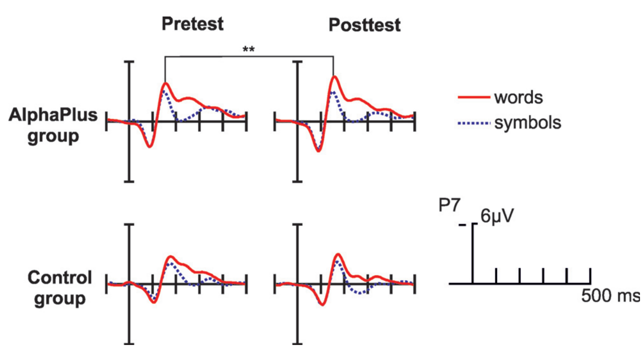

Figure 2. Grand average ERPs time-locked to the onset of stimuli of functionally illiterate adults before and after 9 months of literacy training. The left occipito-temporal electrode (P7) is shown; negativity is plotted up and each tick mark represents 100 ms of activity.

Denckla, Kaufmann & Cutting, 2010; Steinbrink et al., 2008). These differences are attributed to structural deficits of the left superior longitudinal fasciculus and the left arcuate fasciculus (see also Vandermosten, Boets, Wouters & Ghesquière (2012) for a meta-analysis). Further studies also identified other fiber tracts such as the posterior part of the corpus callosum or the inferior longitudinal fasciculus (Ben-Shachar, Dougherty & Wandell, 2007; Dougherty et al., 2007; Rollins et al., 2009; Steinbrink et al., 2008). These structural changes are supported by functional imaging studies showing a disruption of the functional integration between frontal and temporal brain regions (Shaywitz et al., 2003; van der Mark et al., 2011), which is also present at rest (Schurz et al., 2015). In addition to white matter tracts, gray matter has been shown to be altered in dyslexia as well. A common method to investigate changes in gray matter volume is voxel-based morphometry (VBM). VBM allows a voxel-by-voxel comparison of local tissue concentrations after the automated separation of gray and white matter and cerebro-spinal fluid (Richlan, et al., 2013). Therefore, VBM is a useful tool to study morphological abnormalities in developmental dyslexia. Reduced gray matter volume was found in bilateral temporoparietal and left occipito-temporal regions (Brambati et al., 2004; Brown et al., 2001; Steinbrink et al., 2008; Vinckenbosch, Robichon & Eliez, 2005); see also Linkersdörfer, Lonnemann, Lindberg, Hasselhorn & Fiebach (2012) for a meta-analysis and Eckert (2004) for a review). Additionally, the observed structural deficits overlap with functional underactivation in the fusiform and supramarginal gyri of the left hemisphere (Linkersdörfer et al., 2012).

Since similarities between dyslexia and functional illiteracy are discussed (see above), we investigated if functional illiterates show similar structural alterations as those found in dyslexic individuals (Boltzmann, Mohammadi, Samii, Münte & Rüsseler, 2017). Using DTI and VBM, we compared gray and white matter volumes of functional illiterates with a group of normally reading adults. Regarding DTI data, we found that the left genu of the corpus callosum showed significantly reduced FA in functional illiterates before training compared to control participants. After training, FA values increased in this region in functional illiterates compared to the same group before training. Importantly, the increase in FA in the left genu of the corpus callosum correlated positively with the increase in reading ability. Additionally, gray matter intensity was lower in functional illiterates before training compared to controls in left and right supramarginal gyrus, left and right angular gyrus, left and right precuneus, left and right superior parietal lobule and left parietal operculum. After training, we found an increase of gray matter intensity in functional illiterates in the same regions found to be reduced prior to the training (see Fig.3). In some of the regions identified in the previous analyses we found a significant correlation between gray matter intensity in functional illiterates and their reading ability as well as their writing ability. Altogether, the results suggest that intensive literacy training modulates gray and white matter in functional illiterates. These findings are in line with previous studies demonstrating training-induced structural changes for dyslexic children (Krafnick, Flowers, Luetje, Napoliello & Eden, 2014) and complete illiterates (Carreiras et al., 2009).

Functional Brain Changes

It can be assumed that the functional organization of the brain changes when functional illiterates improve their literacy skills. If the changes are similar to those of children learning to read, a shift from frontal and parieto-temporal activations to occipito-temporal activations should be observed. To answer these questions, we conducted an fMRI study (Boltzmann, Rüsseler, Ye & Münte, 2013). Before and after literacy training, participants were shown pairs of words, pseudowords and letter strings on a screen. They were instructed to decide whether both stimuli of a pair rhyme (words, pseudowords) or are the same (letter strings).

Evaluation of the fMRI data revealed higher activation levels for real words and pseudowords relative to letter strings in the inferior frontal gyrus, left postcentral gyrus, left basal ganglia and supplementary motor area (SMA) before training. Inferior frontal regions are usually engaged when words have to be read by grapheme-phoneme-conversion due to unknown or infrequent phonological representations. According to psycholinguistic models, novel readers strongly use grapheme-to-phoneme rules to decode written words. At this level, children consistently activate frontal brain regions comprising the infe-

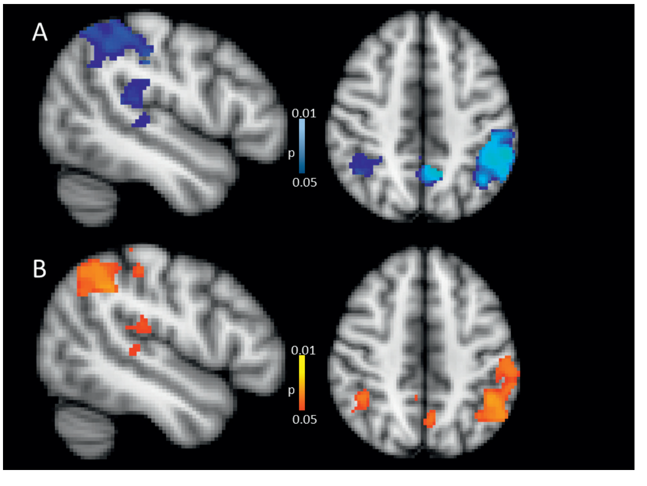

Figure 3. Comparison of grey matter volume between controls and functional illiterates (A) before and (B) after literacy training. All data are FWE-corrected for multiple comparisons.

rior frontal gyrus (Schlaggar et al., 2002; Simos et al., 2001). Frontal brain regions are also engaged when adults have to perform complex phonological tasks (e.g., pseudo-word rhyming) and when they read infrequent words and pseudo-words (Fiebach, Friederici, Müller & Cramon, 2002; Fiez & Petersen, 1998). In addition, areas involved in motor processes were activated when words and pseudowords were presented. These results are in line with previous findings (Kronbichler et al., 2006), and indicate that real words and pseudo-words, both legitimate word forms, invoke speech production processes. In the case of letter strings, on the other hand, no such effect was observed, as here the two strings are compared visually.

Another main finding is related to the fusiform gyrus, which was not activated before training: the occipito-temporal region including the visual word-form area was more activated after nine months of intensive literacy training (see Fig.4). The fusiform region is usually associated with the recognition of familiar orthographical word forms (Binder et al., 2003; Dehaene et al., 2002; Fiebach et al., 2002). Studies found stronger activation for words (Büchel, Price & Friston, 1998; Cohen et al., 2002; Price, Wise & Frackowiak, 1996; Xu et al., 2001) and pseudo-words (Devlin, Jamison, Gonnerman & Matthews, 2006) in contrast to letter strings. According to psycholinguistic models of reading and experimental studies, skilled readers invoke this region to recognize well-known words for which they have developed a visual expertise (for review see (Schlaggar & McCandliss, 2007)).

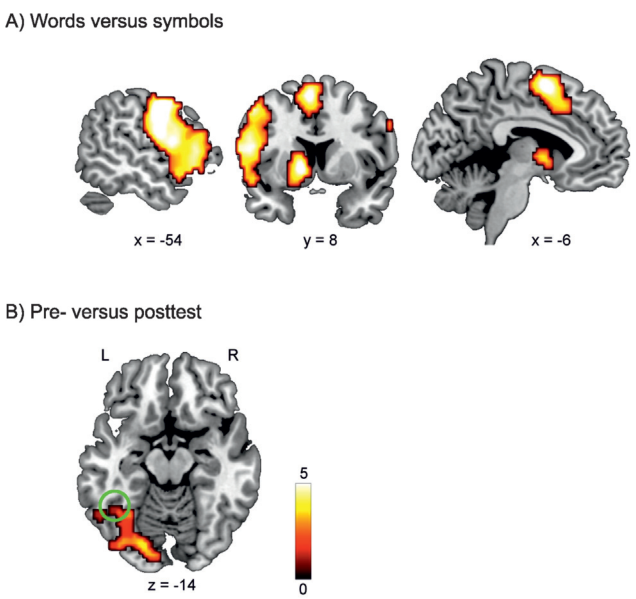

Figure 4. Brain activity modulated by literacy training (after training > before training). Visual word form area is marked with green cycle; L = left; R = right; Coordinates in MNI. Color scale indicates t values.

Conclusion

In Germany, 7.5 Million adults are considered to be functionally illiterate. Functional illiteracy is often associated with specific personal obstacles in childhood concerning school (e.g. truancy, inappropriate instructions, repetition of classes) and family environment (e.g. neglect, drug abuse of parents, abuse, numerous siblings etc.). However, these negative experiences do not apply for all individuals with low literacy skills and are also not sufficient to let someone become functional illiterate (Eme, 2011). Accordingly, some researchers propose that functional illiteracy results from cognitive deficits coupled with environmental disadvantages (Eme, 2011; Greenberg et al., 1997; Greenberg & Ehri, 2002; Grosche, 2012).

Following this point of view, we assume that problems in different areas, e.g. phonological processing, low-level perceptual functions, and audio-visual integration contribute to the deficits in literacy skills prevalent in functional illiterates. AlphaPlus is a special literacy program for functionally illiterate adults focusing on these deficits. Conventional literacy instructions, which represent the main part of the program, are supplemented by methods targeting specific deficits. The effectiveness of the program has been proven in several studies. Overall, the participation in AlphaPlus significantly improves the literacy skills. These changes were also reflected in neural processing of visual word recognition: the early processing of visual word forms after 170 ms and the involvement of reading-relevant brain regions were altered by the training.

However, intensive literacy training is necessary to induce training-related changes (see (Boltzmann et al., 2013). Several reviews have shown that intensive training programs have proven to be effective in dealing with literacy problems in children. Especially in older and severely impaired children, the interventions must be intensive and long-term to achieve the desired effects (Alexander & Slinger-Constant, 2004). It can be assumed that the same applies to adult functional illiterates.

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History/Historie
Received: February 19, 2019
Revision received: April 03, 2019
Accepted: April 05, 2019

Conflict of interest/Interessenskonflikt
None

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