

1. IMAGES OF THE MULTILINGUAL BRAIN: THE EFFECT OF AGE OF SECOND LANGUAGE ACQUISITION

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Is it the age of second language acquisition (AoA) that primarily determines the manner of cerebral representation of multiple languages in the brain, or is it proficiency? Here, we review recent neuroimaging studies that aimed at investigating AoA effects by comparing early with late (usually with L2 acquisition onset after 6 years of age) bilinguals during a variety of language tasks on a number of languages. Most studies did indeed report AoA effects. Of particular interest is that the region mainly found to functionally differ between early and late bilinguals is the left inferior frontal gyrus, which was modulated during syntactic processing, word generation, and sentence generation. Additionally, differences were observed in gray-matter density of the posterior parietal cortex as well as in right-hemisphere involvement. Interestingly, despite some convergence of findings from a localizational point of view, underlying causes of organizational and functional differences for the effect of AoA on bilingual language processing still remain to be uncovered. Hypotheses currently used for explaining activation differences are described (notably cortical efficiency, executive control, neuroanatomical changes, and right-hemisphere involvement) in relation to AoA and language proficiency.

Introduction

In this review article, we introduce prevailing methods, issues, and major findings with regard to age of acquisition (AoA) effects in multilinguals to distinguish them from those of proficiency (this section). In the next section, we review six early studies using imaging methods, which challenge the traditional view of the impact of AoA on cerebral representation. Further, in the third section, we provide some food for thought by presenting related issues, which may help to specify the influence of AoA independent from the level of proficiency on bilingual processing and the cerebral representation of multiple languages. Finally, we formulate some recommendations for future imaging studies to uncover the particular effect of AoA.

We provide a state-of-the-art overview of images of the multilingual brain related to AoA differences and differences in language proficiency. Different types of

data are now available to portray multilingual individuals with regard to patterns of cerebral language activation: (1) In the neurological literature case reports on differential language loss or recovery in polyglot aphasics are usually interpreted as multiple languages being organized in spatially distinct neural regions within the language-dominant hemisphere (Albert & Obler, 1978; Fabbro, 2001). (2) Cortical electrical stimulation studies (Lucas, McKhann, & Ojemann, 2004) suggest possible differences as well in bilinguals' brain organization of language. (3) However, most research on localization and organization of multiple languages in the brain is now conducted using neuroimaging techniques. Functional imaging techniques such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) are currently used to determine whether different languages activate different language-related brain regions during the performance of a particular language task. Although these techniques are based on different measures (fMRI measures changes in deoxyhemoglobin, and PET, changes in blood flow; see Eigsti and Schuh's (2008) contribution to this volume for a description of different techniques), they provide information about local changes in neuronal activity. One main advantage of fMRI and PET is that they are—unlike previous techniques—not limited to a region of the brain that has been damaged or that is stimulated. Instead, a network of distributed brain areas for language processing could be revealed in both hemispheres including subcortical structures.

In general, the language-processing system is considered as an interacting network of language memory, sensory input, and motor output systems that is mainly left lateralized (Price, 2000). Language memory includes several regions in the inferior and middle parts of the temporal lobe (Mummery, Ashburner, Scott, & Wise, 1999). Brain language regions predominantly related to sensory input independent from modality (auditory or visual) have been identified in posterior superior and inferior temporal regions, including Wernicke's area and inferior parietal regions (Mummery et al., 1999; Price, 2000), whereas those supporting motor output are shown in the insula, prefrontal regions including Broca's area, and other frontal regions supporting task execution such as the anterior cingulate gyrus and the (pre-)supplementary motor area (SMA) (Price, Moore, & Frackowiak, 1996; Warburton et al., 1996). In addition, recent research points to the importance of a frontostriatal circuitry during processes of language generation (Crosson et al., 2003; Grossman et al., 2003).

Some earlier neuroimaging studies (e.g., Dehaene et al., 1997; Kim, Relkin, Lee, & Hirsch, 1997) suggested a partial functional separation of bilingual lexicons in the brain. However, these reported findings have been critically reviewed and reanalyzed, since analysis techniques for functional images have been improved during the recent years (e.g., Francis, 2003, in Hull & Vaid, 2007). Some researchers have expressed doubts as to how adequate the imaging methods available are to date (in particular the spatial resolution in PET and fMRI): Rodriguez-Fornells, Balaguer, and Munte (2006) questioned whether "the spatial resolution of functional magnetic resonance (fMRI) (or positron-emission tomography [PET] would allow us to demonstrate a separation of language representations in bilinguals" (p. 136). For instance, the underlying metabolism measured by fMRI, that is, the effect of

neurovascular coupling, does not allow an exact localization of the activated cell assemblies and therefore may impose some limitations on the question of spatially separated languages. In general, the results of most later imaging studies suggest that second language (L2) processing involves largely the same language-specific cortical areas as native language (L1) processing (for reviews, see Indefrey, 2006; Perani & Abutalebi, 2005).

In current research, many factors have been named that might explain the differential cerebral representations in multilinguals: differences in task (one word vs. sentence processing), language modality (production vs. comprehension), language typology, duration of exposure to each language, and the like. In addition, due to lack of some core information with regard to the participants of the study (e.g., ages at acquisition of L2) and nonuniform assessment of language proficiency in both languages (if at all), some findings are difficult to interpret. The two variables, AoA language proficiency, which attracted most attention in early imaging studies on bilingual participants, could be shown to account for functional modulation in the cerebral representation of languages, and will be briefly described in the next sections.

Age of Acquisition

Since it was developed in the 1960s, the “critical period” concept (Lenneberg, 1967; Penfield & Roberts, 1959) has referred to a period in time during the life cycle when there is greater sensitivity in responsiveness to certain types of environmental stimuli than at other times (Colombo, 1982). The term *sensitive period* is preferred by neurobiologists over the widely used term *critical period*, because the former term implies a softer and more plastic set of developmental constraints and transitions than the latter term. The notion of a critical period for language has been invoked to explain differences between learning of L1 and L2, to account for age-related changes in recovery of language abilities following left-hemisphere injury, and in the imaging literature for differential brain activation patterns. Commonly, an age distinction is made around 6 years between *early* and *late* bilinguals.

The causes of age effects on language performance are controversial: differences between infant and adult learning contexts (Lenneberg, 1967) as well as a biologically based critical period for language acquisition have been suggested. More specifically, at the level of neural representation of L2, performance differences may result from differences in maturation of neuronal systems (Neville & Bavelier, 2002). It is based on the idea that there is an age-related decrease in plasticity for language learning.

Paradis (2004) claimed that processing in early and late bilinguals is fundamentally different, because early bilinguals rely more on implicit linguistic competence during processing of L1 and L2, so that it is not surprising that common cortical regions are activated (Chee et al., 2000; Urbanik, Binder, Sobiecka, & Kozub, 2001). Language processing of late bilinguals, on the other hand, is assumed to be based on declarative memory. The different mnemonic strategies, which are applied

in the process of language acquisition of L1 and of a late L2, may be the causes of differences in brain representation (Paradis, 1994).

Level of Language Proficiency

Essential processing differences, for example, on the level of lexical information between L2 learners and native speakers of that language have been postulated in psycholinguistic models and described as being modulated by proficiency (Dufour & Kroll, 1995; Schreuder & Weltens, 1993).

In imaging studies, the focus has been on two major questions: (1) Is the activation in classical language regions during processing different in the weaker language compared to the stronger language? (2) Are additional regions involved in processing in the weaker language or not? The results reported in the literature seem to be at first contradictory for these hypotheses, but appear to depend on the task for the first and on proficiency level for the second hypothesis. Regarding the first hypothesis, in the weaker language, less activation has been reported in comprehension tasks (Dehaene et al., 1997; Perani et al., 1996), whereas greater activation was observed in production studies (Chee, Hon, Lee, & Soon, 2001; Yetkin, Yetkin, Haughton, & Cox, 1996).

Concerning the second hypothesis, activated brain regions would differ from those used in L1 (Dehaene et al., 1997; Perani et al., 1996; Urbanik et al., 2001) for moderately fluent L2 speakers, while for highly proficient bilinguals, the same brain regions are activated during L1 and L2 processing (Pu et al., 2001; Tan et al., 2003). More widespread cortical activity in L2 has been observed in some recent studies (Calabrese et al., 2001; Marian & Spivey, 2003; Vingerhoets et al., 2003), but not by Klein and colleagues (Klein, Milner, Zatorre, Zhao, & Nikelski, 1999).

The different activation patterns related to proficient and less proficient processing have been suggested to indicate that (1) some linguistic components have to be used more frequently, such as pragmatics or metalinguistics, to compensate for gaps of knowledge in less proficient processing; and that (2) other nonlinguistic concepts might be necessary to allow for L2 nonproficient processing: namely, control and monitoring (Paradis, 2004). In the same vein, L2 processing has been described as (3) less automated and thus more effortful, resulting in higher brain activity (e.g., De Bleser et al., 2003).

The principal question of earlier studies was to determine whether, during L1 and L2 processing, the observed activation of brain patterns reflects overlapping or separate language activation. The conclusion was drawn that an L2 learned later in life and mastered with lower proficiency exhibited nonoverlapping activation in language-related cortical regions (Dehaene et al., 1997; Chee et al., 2001; Vingerhoets et al., 2003). On the other hand, when proficiency is high, the prevailing pattern of languages acquired at different ages is one of overlapping rather than separate neural circuitry underlying L1 and L2 performance, both for single-word

paradigms (Pu et al., 2001) and tasks engaging sentence- and discourse-level processing (Chee et al., 1999; Perani et al., 1998).

The results of the imaging studies just described suggest that the effect of AoA may not be separated from the one of proficiency level (see also Birdsong, 2006). This assumption is challenged by a number of recent studies, described in the next section, which elaborated on approaches to detect an effect of AoA at the neuronal level. Most of these studies investigated lexical retrieval (Perani et al., 2003), grammaticality and syntax judgment (Wartenburger et al., 2003), and sentence production (Mahendra, Plante, Magloire, Milman, & Trouard, 2003) with regard to age of L2 acquisition, providing additional support for the much discussed study of Kim and colleagues (1997), which suggested a significant AoA effect for language production at the discourse level.

Review of Recent Studies Investigating AoA Effects in Bilinguals

In this section we present *recent* imaging studies on multilinguals that separate the effect of AoA from other variables of language acquisition and learning, in particular, the level of proficiency. Four of the selected studies compared early with late bilinguals, one study compared earlier with later age of L2 acquisition in early bilinguals, and the last study compared the influence of the age of the participant on L1 and L2 processing in late bilinguals. An interesting study by Ofan and Zohary (2007) will not be considered here, because despite the fact that they used fMRI to compare early and late bilinguals (Hebrew L1 and English L2), their main research question was whether a critical period restricts reorganization of the visual cortex in blind bilinguals.

Comparison of Early with Late Bilinguals

Wartenburger and colleagues' study (2003) compared early (from birth up to age 6) and late (after age 6) Italian-German bilinguals with different levels of proficiency (early high-, late high-, and late low-proficient bilinguals) performing a grammatical and a semantic judgment task. History of language exposure and actual exposure were reported for all subjects. Proficiency was assessed using a language comprehension test and an accredited language proficiency test. The following main findings were reported in their study: In early high-proficient bilinguals no differences in L1 and L2 brain activations were observed during grammatical and semantic judgment tasks. Conversely, late high-proficient bilinguals used the same perisylvian language areas for L1 and L2 judgment, but—in particular during grammatical judgment—they appeared to use additional neural resources, notably in the inferior frontal gyrus and the basal ganglia. In addition, the L2 of late high-proficient bilinguals showed higher bilateral activation in Broca's area (BA 44 and 44/6) than early high-proficient bilinguals, but only during syntactic processing. In contrast, proficiency was revealed to be a determining factor modulating the pattern of brain activity as observed by greater L2–L1 differences in the late low-proficient than in the late high-proficient bilingual group, in particular, during the semantic judgment task.

In their study, Wartenburger and colleagues (2003) were able to disentangle mechanisms responsible for acquisition and processing of grammatical and semantic knowledge, which is compatible with the hypothesis that implicit and explicit learning relies on different neuronal processing. Importantly, AoA could be related to inferior frontal and striatal activation elicited by grammatical judgments in L2. In addition, the authors argued that early (high-proficient) bilinguals may select and use a more available and “automatic” L2; in late bilinguals, processing in L2 may use a less efficient representation and therefore needs greater effort or requires compensatory strategies.

Frenck-Mestre and colleagues (Frenck-Mestre, Anton, Roth, Vaid, & Viallet, 2005) investigated brain activation during speech articulation in early versus late bilinguals by testing word and sentence repetition. French and English bilinguals were examined: Half were early bilinguals (from birth), and half had learned French after the age of 12. Regarding the history of language learning, the authors reported that in all bilinguals both languages had been actively used for years. In the late bilinguals, however, prosody was not nativelike. Early and late bilinguals were referred to as proficient, but without further specification of the level of proficiency in each group. In both groups, overt articulation of words as well as of declarative sentences compared with a baseline of nonword strings resulted in identical bilateral activation of the motor cortex, basal ganglia, cerebellum, and supplementary motor area, independent of the language tested. In late bilinguals, greater variation between L1 and L2 activation was only found in one region of the left basal ganglia (putamen) during word articulation than in early bilinguals. It has to be noted that variable activation in the putamen of late bilinguals always affected both languages.

In this study, proficiency level in early and late bilinguals has not been considered as an interacting variable. In contrast, hypothesizing that increased putamen activation would reflect greater articulatory effort in the less dominant language (L2), activation patterns in the putamen were analyzed in detail, although this region did not evidence reliable task-related activation in both groups at the statistical threshold applied. Accordingly, differences between both groups revealed in the putamen were exclusively discussed in the context of variable articulatory task demands. To reveal effects of AoA, Frenck-Mestre et al. (2005) evaluated brain regions according to a functionally/neuroanatomically constrained hypothesis, not at least because more sensitive thresholds of evaluation are possible. The authors proposed that more variable activation in the putamen of both languages of late bilinguals as compared to those of early bilinguals indicates more generalized changes in language processing.

Mahendra and colleagues (2003) investigated word fluency as well as sentence generation in two languages of early (before age 6) and late (after age 6) bilinguals. Only subjects who considered themselves as fluent have been considered for the study. For characterization of the subjects' fluency, parameters of language instruction, and use are reported. Proficiency level has not been tested. The observed AoA effect was that early bilinguals show higher activation (a greater number of activated voxels) in the left inferior gyrus and left temporal gyrus than late bilinguals,

especially during sentence generation. It has to be noted that only these two classical language regions have been considered for analysis. Interestingly, changes affected both L1 and L2. Early and late bilinguals exhibited differences in threshold activation of the putamen, but the authors did not further elaborate on this finding. The explanation for higher neuronal activity in early bilinguals is based on linguistic considerations: Early simultaneous learning of two languages in early bilinguals may cause them to be more often in a bilingual mode than late bilinguals. This view refers to a concept described by Grosjean (1982). Mahendra et al. (2003) argued that apart from the learning situation, the different speech environments of early and late bilinguals are relevant as well. Early bilinguals are surrounded by bilinguals using both languages (thus being in a bilingual mode), whereas the language setting for late bilinguals is more likely to be monolingual (resulting in late bilinguals being in a monolingual mode). Furthermore, the authors proposed that the higher activation in both L1 and L2 of early bilinguals may be conceptualized as greater overall engagement of brain resources linked to functional differences in language use. Their explanations are not indicative of any functional specialization of the differentially activated regions.

Mechelli and colleagues (2004) used voxel-based morphometry (VBM) to investigate whether the neuronal structure of the human brain is altered by the experience of acquiring an L2 (note that this technique does *not* use *functional* imaging such as fMRI). In a first session, native English bilinguals (with different European languages as L2) were compared to monolinguals. The bilingual group was divided into early bilinguals (L2 acquisition before age 5) and late bilinguals (L2 acquisition between the ages of 10 and 15). VBM analysis revealed greater gray-matter density in the inferior parietal cortex in bilinguals (in particular, in early bilinguals) than in monolinguals.

In a second session, native Italian bilinguals who had learned English between the ages of 2 and 34 were examined. The proficiency test in L2 included reading, writing, speech comprehension, and production. Here, VBM analysis revealed that gray-matter density in the inferior parietal cortex decreased as the AoA increased, but increased with L2 proficiency.

The study demonstrated both an AoA effect as well as an L2 proficiency effect and points to the impact of both L2 acquisition and performance on the degree of structural reorganization in bilinguals, leaving open the question of which more specific changes (e.g., neuronal size, or dendritic or axonal arborization) might cause gray-matter reorganization. The authors proposed that the specific cortical region that was exhibiting changes in gray-matter density is known to be functionally relevant during verbal fluency tasks. Overall, the observed effect is mainly related to language performance, leaving aside explanations of the age factor.

Comparison of Earlier with Later Age of L2 Acquisition in Early Bilinguals

Perani and colleagues (2003) aimed at delimiting effects of AoA from those of language usage or exposure on the cerebral correlates of lexical retrieval. Their

study examined two groups of early high-proficient Spanish-Catalan bilinguals: “Catalan-born” or “Spanish-born” according to the language acquired first. Because the subjects had been exposed to L2 when entering kindergarten, at 3 years of age, they were all “early bilinguals,” but with one language being acquired earlier than the other. The level of proficiency was assessed by a comprehension test, parameters of language exposure, and present use of each language reported. The authors observed an AoA effect when generating words in the language acquired second, even though this language was reported to be mastered to equal levels of proficiency with regard to comprehension. Additional neural resources were involved in the left inferior frontal gyrus, but also in the basal ganglia and other parietal and prefrontal brain regions.

In addition, more extensive activation (in particular, in left prefrontal cortices) was found in the group of Catalan-born subjects than Spanish-born subjects when producing in their L2. The two groups differed in their self-reported amount of usage of and exposure to L2: In the case of the Catalan-born subjects, L2 Spanish was less intensively used than Catalan for the Spanish-born group. This is the first study that provides evidence that both age and amount of exposure to a language may affect the extent of activation during a lexical search-and-retrieval task (see also de Bot, 2008, for a discussion of this problematic aspect of AoA). In this study (Perani et al., 2003), less extensive activity in the left prefrontal cortex was discussed in the context of selection and use of a more “automatic” language. In the same vein, they proposed that decreases in left prefrontal activity might be a sign of decreasing dependence on controlled processing. These functional changes may reflect modulation in neuronal connections and may be induced by repeated activation due to higher exposure. The authors emphasized that different neural resources could act on processing of L1 and L2, but also discuss that cerebral differences may become apparent in specific language tasks only. In this study (Perani et al.), highly proficient bilinguals were selected on the basis of a language comprehension test and are tested by fMRI during a language production task. One could question whether group selection might have been optimized using more adequate language proficiency tests.

Comparison of the Influence of the Age of the Participant on L1 and L2 Processing in Late Bilinguals

Tatsuno and Sakai (2005) introduced a new dimension of the AoA discussion: The authors aimed at disentangling the effect of age (of the participant) from two other variables, proficiency and task demands for L1 and L2. fMRI was used to assess cortical activation during past-tense identification and verb identification in two groups of Japanese-English late bilinguals, at ages 13 (~ school-age) and 19 (~ adolescent) years. Participants of both groups were 12 years old when they started to acquire L2. For the study (Tatsuno & Sakai, 2005), they were divided into subgroups of higher and lower proficiency for each language according to performance in a past-tense identification task. The age of the bilingual subjects was taken as a group criterion with the intention to separate effects of variable proficiency and task demands from effects of age, not only for L2 but also for L1.

Cortical activation involved in regular and irregular past-tense verb identification was compared with the one involved in verb matching.

A clear effect of age (but not necessarily age of L2 acquisition) on task-related activity in the triangular part of the left inferior frontal gyrus was revealed for L1 (Japanese). Here neuronal activity was significantly greater in the 13-year-olds than in the 19-year-olds, despite the matched performances in L1. Additionally, only in the age 19 group was higher proficiency in L2 correlated with lower activation in the triangular part of the left inferior frontal gyrus (BA 44) during past-tense processing in this language. It was argued that the left inferior frontal gyrus shows higher or lower activation depending on which stages of L2 acquisition are compared. Alternatively, left inferior frontal gyrus activation could depend on exposure to the language at a particular stage of the developing brain. Higher activity in this cortical region during L1 and L2 processing may specifically reflect the (control) demands of retrieving past-tense words or the specialization of this area in syntactic processing and language-specific functions that are critically acquired, when mastering any language, rather than functions associated with general changes in cognitive development.

Tatsuno and Sakai (2005) based their results on two groups of subjects, which were different in age but acquired L2 at a similar age (age 12). Accordingly, L2 processing differences between the two age groups that could be captured in the left inferior frontal gyrus do not reflect the effect of age at acquisition, but highlight the importance of different stages of language learning.

Conclusions from the Studies Presented Here

Brain region. Almost all the studies (except Mechelli et al., 2004) reported an effect of AoA in left prefrontal regions. There is strong evidence for an age effect on the basal ganglia (Frenck-Mestre et al., 2005; Mahendra et al., 2003; Perani et al., 2003; Wartenburger et al., 2003) as well, but only Frenck-Mestre et al. (2005) further evaluated this brain region.

Task. The effect of AoA becomes noticeable during syntactic judgment (Wartenburger et al., 2003); word production, including possibly articulation (Frenck-Mestre et al., 2005; Perani et al., 2003, Mahendra et al., 2003); sentence production (Mahendra et al., 2003); and past-tense generation (Tatsuno & Sakai, 2005), indicating its association to executive aspects of language processing.

Proficiency as confounding variable. Proficiency tests have been carried out in all studies reported except in Frenck-Mestre et al. (2005). Different levels of proficiency have been included in the discussion. Because different proficiency tests were used, comparisons of the studies are difficult.

Languages affected. Most studies clearly indicated that both languages of the subjects are affected by the age effect (Frenck-Mestre et al., 2005; Mahendra et al., 2003; Mechelli et al., 2004; Tatsuno & Sakai, 2005),

The imaging studies presented here suggested an effect of AoA. They proposed an attractive approach to this aspect of bilingual language processing. However, a closer look at the testing conditions and analysis procedures indicates that this is only the first step. Overall, factors being directly linked to the effect of age such as the sensitive time period, parameters of language proficiency, stages of language learning, and language contact and use have not been consistently taken into consideration. In this context, it has to be noted that there is need for a proficiency evaluation test, which can serve as standard to compare different studies (for a discussion of this point, see also de Bot, 2008). Moreover, the effect of AoA is mostly discussed very generally, that is, as more effortful processing (Frenck-Mestre et al., 2005; Perani et al., 2003), or as a consequence of social experience (Mechelli et al., 2004). It is explained in the context of linguistic issues (Mahendra et al., 2003) or confounded by arguments, which apply to proficiency (Mechelli et al., 2004) or amount of exposure (Perani et al., 2003).

Several studies, however, named neuroscientific hypotheses to explain effects of age—that is, automatization (Wartenburger et al., 2003), control (Perani et al., 2003), and efficiency (Wartenburger et al., 2003)—but were reserved in further elaborating on their ideas. It is still a domain of active research to examine neuroscientific hypotheses of bilingualism using imaging techniques (see next section).

Neuroscientific Hypotheses in Connection with Bilingual Language Activity

As previously discussed, in most imaging studies on bilinguals, including those investigating AoA effects, it is claimed that multilinguals use overlapping brain regions for their different languages (for a discussion of this point, see also Green, 2008, in this issue). The idea of a common neuronal substrate for different languages in bilinguals is guiding investigations related to four important issues: *cortical efficiency*, *cognitive control*, *neuroanatomical changes*, and *right-hemisphere involvement*, which will be introduced now.

Cortical Efficiency

The concept of cortical efficiency implies that higher ability in a cognitive task is associated with more efficient neural processing. Using electroencephalography (EEG), it has been shown that higher performance in several tasks, including verbal (Parks et al., 1988), numeric, figural, and spatial reasoning (Lamm, Bauer, Vitouch, & Gstattner, 1999), correlates with reduced consumption of energy in several brain regions.

Cortical efficiency in subjects with higher IQ scores has also been found, as the amount of EEG alpha band (7.5–12.5 Hz) background power decreases during cognitive activity compared with a resting state, indicating a more efficient processing strategy for a cognitive task (Neubauer, Grabner, Freudenthaler, Beckmann, & Guthke, 2004).

Reiterer and colleagues (Reiterer, Hemmelmann, Rappelsberger, & Berger, 2005) suggested that acquisition of an L2 is equivalent to training of a cognitive-behavioral skill, and they proposed to use the cortical efficiency paradigm to interpret an EEG coherence study on the effects of proficiency in L2 on language processing. Coherence of the EEG signal between different brain regions during L1 or L2 processing was compared in two groups of bilinguals differing in proficiency in L2 (despite the same age of L2 acquisition). EEG was recorded during auditory perception of a linguistic stimulus: Multimodal speech was presented in language videos with speakers visibly articulating and gesticulating to simulate natural communication. Group differences were observed in particular in the 8–10 Hz frequency EEG band (low alpha band); coherence brain maps revealed more pronounced and widespread increases in coherence in low-proficient than in high proficient L2 speakers. Interestingly, changes were observed not only during L2 but also during L1 processing as well. Reiterer and colleagues proposed that the different processing of L1 as well as L2 between high- and low-proficient bilinguals is related to fundamental differences between the two groups in terms of general language processing, listening comprehension skills, or cognitive control. Highly proficient L2 speakers might apply more efficient or more focused linguistic strategies, maybe as a consequence of more sophisticated language training and knowledge. The authors also suggested that decreases in low alpha coherence in high-proficient bilinguals that have been observed in prefrontal regions could indicate intensified cooperation of the prefrontal cortex with subcortical regions, and thus increased automatic processing. Do imaging data signalize higher or lower neuronal activity with more automatic or efficient language processing? In bilingual studies on proficiency, the most prominent explanation for behavioral differences is how automatic (i.e., rapid, effortless, unconscious, and ballistic) the processing in the relevant language is (Clahsen & Felser, 2006; Segalowitz & Hulstijn, 2005). Segalowitz and Hulstijn reviewed the research on automaticity in bilingual language processing and claimed that practice and experience with a language typically lead to faster processing, which is reflected in various ways, for example, faster lexical decision times and fewer errors. Later phases of L2 learning therefore seem to involve automatic processing to a far greater degree than do earlier phases. Perani et al. (2003) argued that the same explanation would hold for the observed pattern of less L1 as compared to L2 activation due to “environmental exposure”: Generating words in L1 is claimed to be a more automatic task than in L2. On the cerebral level, this difference would be reflected by the engagement of fewer neural resources. This explanation is supported by results of imaging studies in which a monolingual, less automatic cognitive task engaged more cerebral resources (e.g., Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997). Does “more automatic processing” also entail “less effortful processing” and thus need for fewer neural resources? Increases in cognitive demands during task execution have been observed to be reflected in imaging data by means of stronger activation of cerebral structures. For example, efforts for syntactic processing produce a strong activation in the inferior frontal gyrus (IFG; see Bookheimer, 2002). Further, Jeong and colleagues (2007) and Hernandez and Meschyan (2006) reported an increased activity in the right insula, the anterior cingulate gyrus (ACC), the dorsolateral prefrontal cortex (DLPFC), and the left fusiform gyrus for naming pictures by late bilinguals in L2 compared to naming in L1. Indefrey (2006)

suggested that the neuronal organization of the IFG might be, in some way, optimized for L1 and thus less efficient for later learned languages. He provided two possible explanations for its observed stronger activation in L2 processing: (1) related to behaviorally measurable performance to compensate for lower efficiency and higher task effort and (2) related to neuronal processing to compensate for lower efficiency of neuronal organization, because quantitatively more neurons are needed to perform the task. Indefrey (2006) proposed that efficiency of the neuronal organization might improve in the course of L2 acquisition.

Cognitive Control

Learning of an L2 influences specific cognitive skills. Rodriguez-Fornells and colleagues (2006) provided deeper insights for the understanding of cognitive control being involved in bilingual language processing. In their review, they summed up the control network as including left DLPFC/ACC-SMA. These brain regions have been suggested to be involved in different aspects of executive functioning (see Curtis & D'Esposito, 2003), for example, selection of different response alternatives, task switching, prevention of interference, and inhibition of irrelevant information. In particular, the ACC has been claimed to evaluate the demand or need for cognitive control by monitoring for the occurrence of conflict or interference (Carter et al., 1998). The degree of cognitive control that is necessary for successful task execution was reflected by increased fronto-central negativity of event-related potentials (ERPs) (Balaguer, Sebastián-Gallés, Diaz, & Rodriguez-Fornells, 2005) and has been found to depend on (1) task difficulty or complexity and (2) individual differences in the speaker's ability, for example, proficiency in L2, and the level of interference of the nontarget language (Rodriguez-Fornells et al., 2006).

In Abutalebi and Green (2007) a speculative answer can be found for the reason why differences in proficiency might affect the degree of left prefrontal activation. When L2 is mastered at a low degree of proficiency, processing is strongly controlled; processing of a language at a high level of proficiency is, in contrast, automatic. Nonautomatic processing requires higher activity in the left prefrontal cortex; it is conscious and effortful, and entails cognitive control processes (e.g., Segalowitz & Hulstijn, 2005).

Neuroanatomical Changes

Several studies have provided evidence for experience-based structural changes in the brain of bilinguals (for discussion, see also Green, Crinion, & Price, 2006). One currently applied computational neuroanatomy technique is voxel-based morphometry (VBM), which captures differences in the local composition of brain tissue after eliminating macroscopic changes in brain shape. VBM identifies differences in gray or white matter based on structural magnetic resonance (MR) images. This approach is sensitive to small-scale differences in the concentration or volume of different types of neural tissue. VBM analyses have provided evidence for effects of practice on gray-matter density, for example, when playing a keyboard instrument (Gaser & Schlaug, 2003). With regard to language, the results of a recent

study (Lee et al., 2007) suggest that for monolingual English adolescents, vocabulary knowledge is a variable that predicts gray-matter density in the posterior supramarginal gyrus. VBM measures in bilinguals are based on the claim that in bilinguals a common substrate is involved in language acquisition and processing. In the left posterior supramarginal gyrus, increased gray-matter density in bilinguals as compared to monolinguals has been interpreted as adaptive changes due to the acquisition of an L2 (Mechelli et al., 2004): Both high proficiency in L2 and early L2 acquisition have an impact on gray-matter density of this cortical region. Results of this study have been corroborated by an investigation on processing unfamiliar speech sounds (Golestani, Paus, & Zatorre, 2002). Here, fast L2 learners evidenced higher gray-matter density in left parietal regions.

Using magnetic resonance imaging (MRI), Coggins and colleagues (Coggins, Kennedy, & Armstrong, 2004), when comparing monolingual and bilingual subjects, revealed further anatomical changes of the brain. The authors attributed changes in the size of the corpus callosum (anterior midbody) to bilingualism, suggesting that the morphology of the bilingual brain has to adapt to multiple language processing. But they did not address specifically the relationship of corpus callosum variability between mono- and bilinguals to age of L2 acquisition.

Right-Hemisphere Involvement

Hull and Vaid (2007) hypothesized that right-hemisphere involvement distinguishes early from late bilinguals, thereby reviving the well-known discussion on lateralization language processing in bilinguals. In their recent meta-analysis of behavioral data, Hull and Vaid carefully assessed the effects of various variables of L2 acquisition on language representation in the brain, that is, the influence of AoA (age hypothesis) and of proficiency (stage hypothesis). They reanalyzed behavioral laterality studies that focused on the relationship between active language performance and the hemisphere to which stimuli were presented to infer hemisphere participation on language tasks. In infant-onset bilinguals (both languages are acquired by age 6), the authors observed consistently similar patterns of bilateral activation for L1 as well as for L2. When L2 was learned later, that is, in childhood (ages 6–13) or adulthood (after the age of 13), left hemisphere (LH) lateralization was found for both languages. Investigation of the lateralization hypothesis showed a stronger effect for AoA than for proficiency level. Hence, Hull and Vaid's analysis was considered highly valuable for the subject of the present research, even though it is not yet clear whether experimental lateralization studies have the same weight as data from aphasia and neuroimaging studies (for a critical discussion of this point, see de Bot, 2008). Hull and Vaid put forward the “anchoring hypothesis” that the functional lateralization of the first language that is set up in the brain during early development anchors the organization of subsequently learned languages: When one language of infant-onset bilinguals is bilaterally organized, so is the other; likewise, when the L1 of late bilinguals is LH dominant, so is L2. Consequently, the effects of bilingualism onset age as a predictor of bilingual laterality remain unchanged when modeled by other subject variables such as proficiency in L2, experimental paradigm, English as L2, and tested language aspect. In their study, Hull and Vaid revealed the

role of AoA on aspects of neuronal language representation in bilinguals, proposing a new approach to how to estimate the impact of AoA. In fact, they argued that within the subgroups of early and late bilinguals, L1 and L2 use the same neuronal circuits with respect to an anatomical or functional criterion, namely, hemisphere lateralization. Thus, Hull and Vaid investigated effects of age of L2 acquisition within the conceptual framework of an anatomically or functionally constrained hypothesis.

Going one step further, Hull and Vaid (2007) proposed that organization of subsequently learned languages depends on the functional lateralization of first language(s) (early = bilateral, late = LH), suggesting that an L3, L4, and so on, should follow the same pattern uncovered here for L2. A recent imaging study (Briellmann et al., 2004) provides supportive evidence for the anchoring hypothesis: They tested the variations in multilingual onset-ages among quadrilingual participants. Hull and Vaid noted that, when examining representative slices for each individual in Briellmann et al.'s study, the infant-onset multilingual showed virtually identical bilateral activation for all four languages, including the language in which proficiency was low, whereas late multilinguals showed more LH (relative to right hemispheric [RH]) activation overall, and all but one showed increasing amounts of activation as proficiency in the foreign language decreased.

Hull and Vaid (2007) put forward three possible explanations for greater RH involvement in early bilinguals: (1) metalinguistic knowledge needs to be developed and applied; (2) different aspects of language processing (phonology, grammar vs. pragmatics) might be differentially sensitive to AoA (see also Paradis, 2004, who argued that nondominant hemisphere involvement is a combination of implicit or explicit and pragmatics vs. lexical-syntactic processing); and (3) due to greater amount of experience with handling two language systems, early bilinguals intensify or accelerate the automatization of language processes.

Recommendations for Further Imaging Studies on the Effect of AoA

Distinguish AoA and Proficiency

As this review of the effect of AoA on the cerebral organization of multiple languages shows, proficiency is still too much entangled in research designs as well as in discussions when AoA effects should be explained. Recent bilingual language production studies using fMRI strongly suggest that when proficiency is taken as a different rather than as a confounding variable, and is controlled for, AoA effects can be observed. In this context it has to be pointed out that low or even lost proficiency in the early bilingual's languages has not been studied much so far. This aspect has only been considered by Pallier and colleagues (2003). Using fMRI, the authors investigated Korean subjects that have been adopted during childhood and had not been exposed to Korean (their L1 from infancy). Interestingly, the pattern of L1 brain activity revealed resembled that of an unknown language.

Determine the Aspect of Cortical Organization That Is Influenced by Age of L2 Acquisition

The question remains: What is so different at the cerebral level when an L2 is acquired later than during early childhood? Future studies trying to come closer to the answers to why two languages might be organized differently when later acquired, and how they differ with regard to processing would allow for clear-cut distinctions between the effects of proficiency and AoA. To our knowledge, currently only three factors were clearly suggested to be modulated by AoA: (1) the difference in memory-representation of grammar and semantics (Paradis, 1994, supported by the study by Wartenburger et al., 2003), (2) the difference in gray-matter density (put forward by Mechelli et al., 2004), and (3) the differential involvement of the right hemisphere (claimed by Hull & Vaid, 2007).

Despite the fact that many studies have described different patterns of bilingual language behavior, interpreted as AoA effects or proficiency differences, unfortunately the discussion of these effects mostly did not include a consideration of the cognitive processes on which these behavioral differences might be based. To date, one cannot find any satisfactory description, which specific cognitive mechanisms or processes are so particularly difficult for older learners (late bilinguals) in contrast to early bilinguals. In one very remarkable attempt, however, to provide hints for processing differences Clahsen and Felser (2006) claimed that late L2 learners have particular difficulty with processing hierarchical representations (e.g., nonlocal dependencies) rather than with grammar processing in general, as has been suggested.

Careful Selection of Tasks for Future fMRI Studies on AoA Effects

We would like to stress the importance of understanding the underlying processes involved in task execution in order to uncover processing differences of early and late bilinguals. Although Paradis (2004) opted for more naturalistic language tasks, Indefrey (2006), in his recent review focusing on L1 and L2 processing, noted that the tasks used in bilingual imaging studies have developed from rather unspecific sentence or discourse tasks to more focused tasks, which actually allow for investigating specific language processes and underlying cognitive processes. One such example is the study by Hernandez and Meschyan (2006), who attempted to detect the underlying cognitive processes that differentiate production in L1 versus L2 (focusing on picture naming). In his review, Indefrey (2006) discussed activation patterns during, for example, word-level production in picture naming or verbal fluency to assess in which aspects L1 versus L2 processing was different. Thus, he focused on differences which could be related to specific cognitive processes underlying certain tasks. At present, numerous neuroimaging tests, which have been validated to visualize language processes, have never been studied in the context of the AoA effect. Taking into account that AoA could possibly manifest in corticosubcortical (basal ganglia) circuits, paradigms that focus on these specific brain regions could be interesting to study. One example is the paradigm used to investigate processing of syntactic complexity in Parkinson's disease patients (Grossman et al., 2003).

Adopt a Network View

Abutalebi and Green (2007) remarked that, to date, neuroimaging research supports identifying brain areas involved in bilingual language processing, with a focus on particular structures that were active in certain tasks. They suggested that, more importantly, now it should be investigated how certain regions work together. Neuroimaging researchers should therefore not consider each area individually but adopt a network view for all activated brain regions (Hernandez & Meschyan, 2006). For instance, using whole-brain scans, Stowe and colleagues (Stowe, Haverkort, & Zwarts, 2005) revealed brain regions that had not been shown to be relevant to language processing.

Other Variables: Language Typology and Manner of Acquisition

In psycholinguistic research, additional factors such as language typology and modality of acquisition have been much discussed in particular in the 1980s (see Ellis & Laporte, 1997 for a review) and shown to influence multilinguals' language performance. The effect of language typology on multilingual brain organization is to date not clear; however, this issue has again attracted some attention. Jeong et al. (2007) recently suggested that when L1 and L2 are linguistically similar to each other, L2 processing might draw on efficient linguistic systems used for L1 processing. Thus, the typological distance of two languages of investigated bilingual groups should be carefully considered in future multilingual fMRI studies.

It seems that the confusion about the term *manner of acquisition* is increasing. Modality of acquisition has been named differently: context of acquisition (effects of formal instruction vs. naturalistic exposure), or "manner of learning and language use" (Fabbro, 2001). Based on data from aphasia, Fabbro (2001) claimed that a representational difference could be observed modulated by the context of acquisition. The modalities of a language usually refer to the distinction between reading and writing, as well as speaking and comprehension (and becomes relevant, e.g., when acquiring a dialect, which does not exist in written form). Furthermore, research on explicit and implicit instruction as well as teaching methods (e.g., output practice) led to the investigation of different learning strategies, as well subsumed under the category of *manner of acquisition*, and is still examined in studies on learning an artificial language (Friederici, Seinhauer, & Pfeiffer, 2001). More recently, it seems that other issues were included under the umbrella term *manner of acquisition* and found their way into the imaging literature as possible factors influencing the representation of multiple languages in the brain: environmental exposure (i.e., the amount of active language use such as talking to family and friends) and exposure to certain language varieties (radio, TV), discussed in Perani et al., 2003). Indefrey (2006) attributed great importance to the role of this factor as determining the presence or absence of activation differences between L1 and L2. Jeong et al. (2007), for example, reported a significant negative correlation between brain activation during Japanese processing in the left caudate nucleus and the duration of stay in Japan for the Chinese L1 speakers. The duration of language use

has been mentioned (Hull & Vaid, 2007), which might explain the activation patterns reported in the study of Tatsuno and Sakai (2005) to some degree.

From our description of the various factors that may influence the cerebral organization of multiple languages in the brain, it becomes apparent that detailed psycholinguistic investigations of participating subjects are necessary. Such clarifications would allow us to describe the sample studied in order to compare results across different imaging studies on effects of AoA and exclude confounding variables. Then, its very own effect of AoA on representation of a multilingual's languages may become clear.

ANNOTATED REFERENCES

Hull, R., & Vaid, J. (2007). Bilingual language lateralization: A meta-analytic tale of two hemispheres. *Neuropsychologia*, 45, 1987–2008.

Hull and Vaid presented a meta-analysis of behavioral laterality studies and assessed effects of various variables (AoA, proficiency in L2) of L2 acquisition on language representation in the brain. The authors observed consistently similar patterns of bilateral activation for L1 as well as for L2 in infant onset bilinguals (both languages are acquired by the age 6). When L2 was learned later, that is, in childhood (ages 6–13) or adulthood (after the age 13), LH lateralization was found for both languages. The authors put forward the “anchoring hypothesis” that the functional lateralization of first language that is generated in the brain during early development anchors the organization of subsequently learned languages.

Kim, K. H. S., Relkin, N. R., Lee, K. M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature*, 388, 171–174.

Kim and colleagues studied early and late bilinguals. Of these, six had been exposed to L1 and L2 learning during infancy (the exact age of L2 acquisition, however, was not provided), and six began learning L2 after puberty. The experimental task required covert language production (discourse). The authors found Broca's area differentially activated for the two groups: overlapping activations for both languages in early learners and spatially segregated activations in late learners. Kim et al.'s conclusion was that AoA is a major factor in the cortical organization of L2 processing.

Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., et al. (2004). Structural plasticity in the bilingual brain: Proficiency in a second language and age at acquisition affect grey-matter density. *Nature*, 431, 757.

Mechelli and colleagues aimed at investigating whether the structure of the human brain is altered by the experience of acquiring an L2.

Therefore, in a first study, native English bilinguals were compared to monolinguals. Voxel-based morphometry (VBM) revealed that gray-matter density in the inferior parietal cortex was greater in bilinguals (in particular, in early bilinguals) than in monolinguals. In a second study, native Italian bilinguals were examined who had learned English between ages 2 and 34. Here, VBM analysis revealed that gray-matter density in the inferior parietal cortex decreased as the AoA increased, but increased with proficiency in L2.

Wartenburger, I., Heekeren, H. R., Abutalebi, J., Cappa, S. F., Villringer, A., & Perani, D. (2003). Early setting of grammatical processing in the bilingual brain. *Neuron*, 37, 159–170.

Wartenburger et al.'s study compared early (from birth up to age 6) and late bilinguals (after age 6) (Italian-German) with different levels of proficiency (early high-, late high-, and late low-proficient bilinguals) performing a grammatical and a semantic judgment task. The comparison of activation patterns between early and late high-proficient bilinguals supports an AoA effect on cortical activations, such that the left inferior frontal gyrus activation for grammatical processing in L2 is greater than in L1. On the other hand, the effects of proficiency levels as revealed by the differences between high- and low-proficient bilinguals appeared to involve both grammatical and semantic processing.

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