Brain & Language xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l

Age of language learning shapes brain structure: A cortical thickness study of bilingual and monolingual individuals

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Anatomical brain imaging
Cortical thickness
Bilingualism
Second-language acquisition
Brain plasticity
Magnetic resonance imaging (MRI)

ABSTRACT

We examined the effects of learning a second language (L2) on brain structure. Cortical thickness was measured in the MRI datasets of 22 monolinguals and 66 bilinguals. Some bilingual subjects had learned both languages simultaneously (0–3 years) while some had learned their L2 after achieving proficiency in their first language during either early (4–7 years) or late childhood (8–13 years). Later acquisition of L2 was associated with significantly thicker cortex in the left inferior frontal gyrus (IFG) and thinner cortex in the right IFG. These effects were seen in the group comparisons of monolinguals, simultaneous bilinguals and early and late bilinguals. Within the bilingual group, significant correlations between age of acquisition of L2 and cortical thickness were seen in the same regions: cortical thickness correlated with age of acquisition positively in the left IFG and negatively in the right IFG. Interestingly, the monolinguals and simultaneous bilinguals did not differ in cortical thickness in any region. Our results show that learning a second language after gaining proficiency in the first language modifies brain structure in an age-dependent manner whereas simultaneous acquisition of two languages has no additional effect on brain development.

1. Introduction

The majority of people in the world learn to speak more than one language during their lifetime. Some do so with great proficiency particularly if the languages are learned simultaneously or from early in development. Age of acquisition effects are also seen in the brain's functional organization of native and second languages (e.g., Fabbro, 2001 and Perani et al., 1996; Vaid & Hull, 2002). Given that the brain is differentially responsive to variations in early sensory experience (Neville & Bavelier, 2002), one might also expect to find evidence for neural plasticity in response to variations in early language experience. Indeed, findings from a variety of sources have been interpreted to suggest that bilingual language experience confers unique patterns of neurofunctional activity and brain structure (e.g. Mechelli et al., 2004).

Studies of individuals who differ in terms of whether they learn one language or two and in terms of the age at which they learn a second language, offer a unique opportunity to explore the potential influence of variation in early *language* experience on the shaping of brain function and structure and its potential for plasticity (see Golestani & Zatorre, 2004; Mechelli et al., 2004). There is also evidence for specific cognitive repercussions associated with early acquisition of two languages such as increased inhibitory control and increased cognitive reserve (e.g., Bialystok, 2002, 2009).

Here, we examined the effects of learning a second language (L2) on brain structure in a large group of bilingual individuals compared to a group of monolinguals. We used automated measurement of cortical thickness from MRI scans to detect anatomical differences among individuals who acquired only one language (monolinguals), individuals who acquired two languages simultaneously from birth or very early in life (0–3 years; simultaneous bilinguals) and individuals who learned two languages sequentially, acquiring the L2 either from early childhood (4–7 years; early sequential bilinguals) or late childhood (8–13 years; late sequential bilinguals). Simultaneous bilinguals constitute an apt point of comparison to monolinguals (similarly exposed to language from early life), hence, permitting the ideal basis for comparing language representation in the bilingual versus monolingual brain. Moreover, inclusion of individuals who ranged in age of L2 acquisition allowed us to distinguish the neurological correlates of simultaneous or early bilingualism as compared to sequential or late bilingualism.

2. Materials and methods

Magnetic Resonance Imaging (MRI) scans from 66 bilingual participants (27 male; 39 female) and from 22 monolingual participants (10 male; 12 female) were obtained (see Table 1 for

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http://dx.doi.org/10.1016/j.bandl.2013.05.014

Table 1
Group characteristics.

	Monolingual ($n = 22$)	Simultaneous Bilingual ($n = 12$)	Early Sequential Bilingual ($n = 25$)	Late Sequential Bilingual ($n = 29$)
Gender				
% Female	55	67	48	66
% Male	45	33	52	34
Mean age at MRI (y)	25	23	26	28
Mean L2 AoA (y)	n/a	1	5	10
Mean L2 experience (y)	n/a	22	21	19
Mean L2 proficiency[a]	n/a	6.3	5.4	5.2

y – Years; L2 – second language; AoA – age of acquisition.
[a] Rating scale from 1 to 7 (lowest to highest).

demographic information). Subjects were healthy right-handed individuals with no neurological history or hearing impairment and were recruited from the Montreal area; groups were matched for education, socioeconomic status and age and were of approximately equal gender ratios. The ratio of males to females in the monolingual and early bilingual groups was almost equal whereas it was nearer two-thirds female to one-third male in the simultaneous and late bilingual groups. A chi-squared test of the male/female ratio across the four groups was not significant (Chi-squared = 1.685, df = 3, $p = 0.64$). Subjects ranged in age at scan from 18 to 48 with a mean age of 26 years. Language background and proficiency was assessed using a self-report questionnaire and a detailed interview. All bilinguals were living in Montreal, a French–English bilingual environment and although all were using both languages in their everyday activities, they ranged in proficiency and in degree of their language usage. This was determined by giving them an in-house questionnaire which ranked on a scale of 1–7 their comfort in their L2 on reading, speaking, writing and comprehension, as well as detailed information about their family linguistic background and language-acquisition history. Given that the data was acquired from multiple MRI studies, only proficiency measures obtained consistently in each protocol could be used. Thus, for the purposes of this study, a global proficiency score was determined for each subject which combined their responses to the questionnaire and the results from a brief objective screening. The bilingual participants ranged in age of acquiring their L2, some having learned both languages simultaneously (age of acquisition <3 years; $N = 12$), and those who have learned the two languages in early childhood (4–7 years; $N = 25$) or late childhood (8–13 years; late sequential bilinguals; $N = 29$). Since age of second-language acquisition is thought to affect the ultimate skill achievable by a speaker (Lenneberg, 1967), the three subgroups were chosen to tease out the differences to be observed in individuals acquiring the language from birth as compared to those acquiring the language early in life and those presumably after a presumed critical period. Simultaneous bilinguals have equal usage of both languages, having acquired each language typically from a parent in a native language context, while the later learned bilinguals generally acquired the two languages sequentially in a more formal language context with there being an equal number of French L1 and English L1 participants. For the monolinguals, none considered themselves to be competent users of any language other than their native one (English) and even though some reported some formal training of another language in a formal language setting such as school, these subjects scored their proficiency ratings for reading, writing, speaking and comprehension uniformly low in any other language of which they had knowledge.

2.1. Procedure

2.1.1. Data Acquisition

T_1-weighted (T1W) whole brain scans were acquired on a Siemens Sonata 1.5T MRI scanner. MR data were combined from multiple studies on bilingualism at the Montreal Neurological Institute. The T1W sequence common across all studies was a 3D gradient echo FLASH sequence: 176 contiguous, 1.0 mm thick axial planes; repetition time (TR), 22 ms; echo time (TE), 9.2 ms; flip angle (FA), 30°; voxel size, 1 mm^3.

2.1.2. Cortical thickness generation

The acquired MR images were processed using the CIVET image processing pipeline developed at the Montreal Neurological Institute (Ad-Dab'bagh et al., 2006) to generate cortical thickness measurements for each subject. This procedure involves processing of the MRI through multiple sequential procedures to provide a measurement of cortical thickness across the entire brain at over 80,000 points (Kim et al., 2005; Lerch & Evans, 2005). First, the MRI was processed to remove non-uniformity artifacts using the N3 algorithm (Sled, Zijdenbos, & Evans, 1998) and then subsequently registered into standardized stereotaxic coordinate based on the Talairach atlas space (Mazziotta et al., 2001) using a 9-parameter linear transformation (Collins, Neelin, Peters, & Evans, 1994). This transformation achieves alignment along the AC–PC axis and accounts for individual differences in global brain volume and shape. Brain tissue was automatically classified (Zijdenbos, Forghani, & Evans, 1998) and deformable meshes were applied to automatically extract the white and gray boundary and the pial surface using the Constrained Laplacian-based Automatic Segmentation algorithm (CLASP) (Kim et al., 2005; MacDonald, Kabani, Avis, & Evans, 2000). Subsequently, native space cortical thickness, measured as the distance between two corresponding points from each cortical surface was computed and blurred using a 20 mm surface-based kernel throughout the cortex (Ad-Dab'bagh et al., 2005; Boucher, Whitesides, & Evans, 2009; Lyttelton, Boucher, Robbins, & Evans, 2007; Robbins, 2004).

2.1.3. Analyses

A series of analyses were performed according to the general linear model: (1) cortical thickness contrasts of groups of bilinguals compared to each other and to a group of monolinguals, and (2) a

Table 2
Peak coordinates of brain areas where cortical thickness and language experience were significantly related ($p < 0.05$).

Analysis	Brain area	x	y	z	t	P
Group differences:						
Late > Mono	Left IFG	−23	26	−17	2.88	0.0029
Late < Mono	Right IFG	30	21	−7	4.13	0.0013
Early > Mono	Left IFG	−27	23	−23	2.51	0.034
Early < Mono	Right IFG	30	19	−11	3.30	0.0043
Native > Late	Right IFG	32	59	−7	3.16	0.0032
Regression:						
Positive correlation	Left IFG	−44	26	−10	2.82	0.0062
Negative correlation	Right IFG	38	57	−2	3.60	0.0022
Positive correlation	Left parietal	−12	−78	49	2.75	0.0072

Mono – Monolingual; IFG – inferior frontal gyrus; x,y,z – coordinates in the space of the Montreal Neurological Institute template; t – t-statistic; P – corresponding p value for t-statistic.

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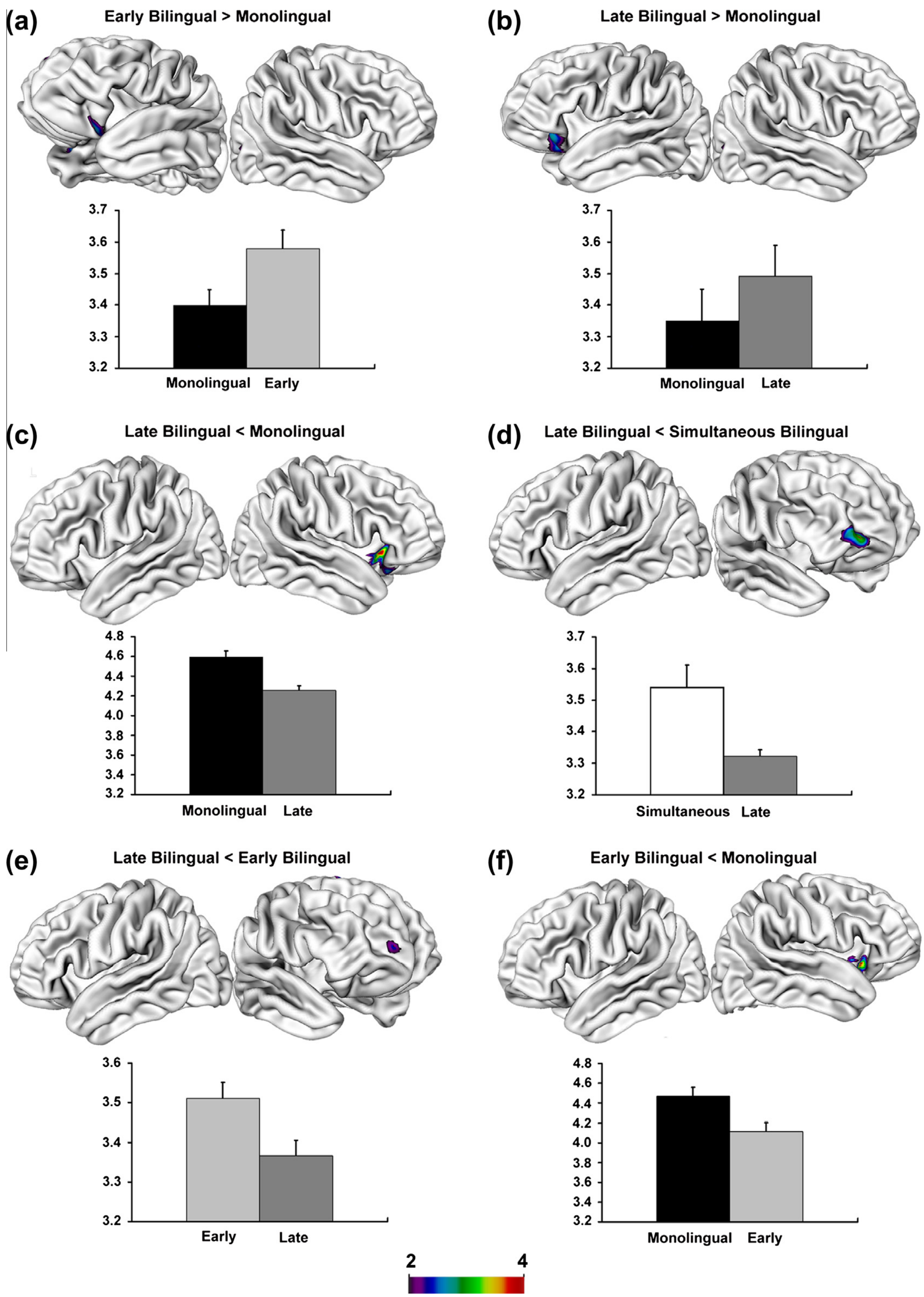

Fig. 1. Group differences in cortical thickness. A color map displayed at a t-statistic threshold of $t > 2.0$ overlaid on the surface of a standardized brain indicating differences between groups in cortical thickness (see Table 2 for a summary of significant results; all peaks were significant after FDR correction at $q = 0.05$). Left inferior frontal cortical thickness is increased in (a) early bilinguals relative to monolinguals and (b) late bilinguals relative to monolinguals. Right inferior frontal cortical thickness is decreased in (c) late bilinguals relative to monolinguals, (d) late bilinguals relative to simultaneous bilinguals, (e) late bilinguals relative to early bilinguals, and (f) early bilinguals relative to monolinguals. For illustrative purposes, histograms for each corresponding subtraction taken from the peak vertex show the mean and the standard error of absolute focal thickness in the left inferior frontal gyrus (a and b) and in the right inferior frontal gyrus (c–f). Legend: Black bars = monolinguals, white bars = simultaneous bilinguals, light grey bars = early sequential bilinguals, dark grey bars = late sequential bilinguals.

series of cortical thickness regression analyses within the group of 66 bilingual subjects taking age of second language acquisition (AoA), proficiency and years of language experience as the main factor in each regression. Although chronological age (CA) ranges were similar across the groups, we observed that CA significantly affects cortical thickness in our sample so we included CA and its

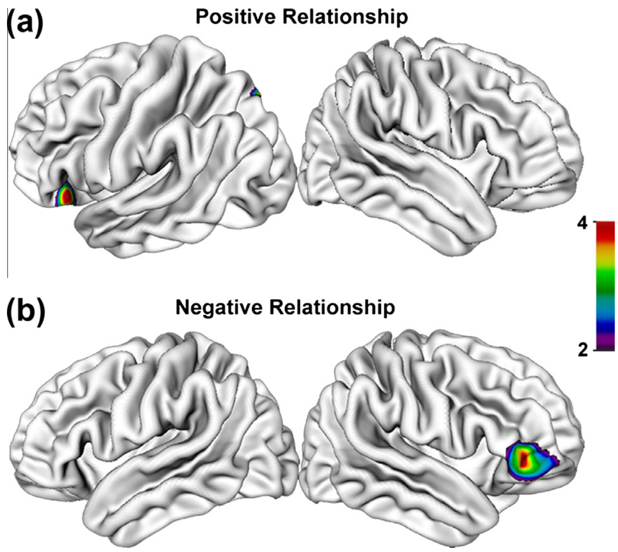

Fig. 2. The relationship between cortical thickness and age of acquisition of the second language in bilinguals. Color map of the *t*-statistic is overlaid on the surface of the standardized brain reflecting a significant relationship between age of acquisition of L2 and cortical thickness within the bilingual group ($n = 66$). See Table 2 for a summary of significant results; all peaks were significant after FDR correction at $q = 0.05$. The linear regression analysis used chronological age, language proficiency in L2, years of exposure in the L2 and the interaction between chronological age and age of acquisition as covariates.

interaction with AoA as covariates in all regression analyses. All statistical analyses were performed using an in-house MNI-developed software package (https://wiki.phenogenomics.ca/display/MICePub/RMINC) that links to the statistical toolkit "R" (version 2.14.1, The R Foundation for Statistical Computing). Statistical thresholds for cortical thickness analyses were corrected for multiple comparisons using the FDR technique (Genovese, Lazar, & Nichols, 2002) at a level of $q = 0.05$. For each statistical comparison, all P values were pooled across all vertices to determine the FDR threshold. Table 2 indicates the locations of (i) significant differences in cortical thickness between groups (top half) and (ii) significant correlations with age of acquisition (bottom half).

3. Results

3.1. Comparison between groups

We first tested for cortical thickness differences among the monolingual and different groups of bilinguals. Two regions showed differences in cortical thickness in relation to the language experience of the groups (Table 2). The anterior aspects (pars triangularis and pars orbitalis) of the left inferior frontal gyrus (IFG) were significantly thicker in both early and late sequential bilingual groups compared to the monolingual group (see Fig. 1a and b). In the homologous region of the right hemisphere, the opposite pattern of results was seen; cortex was significantly reduced in thickness in the anterior right IFG (pars orbitalis) in the late sequential bilingual group compared to the monolingual, simultaneous bilingual and early sequential bilingual groups (Fig. 1c–e). Early sequential bilinguals also showed significantly reduced cortical thickness in this region compared to the monolingual group (Fig. 1f).

3.2. Cortical thickness correlation with age of L2 acquisition

We next investigated the relationship between brain structure and age of acquisition of the L2 in the bilingual participants, controlling for chronological age, language proficiency and years of L2 exposure. Consistent with the results from the group comparisons, a regression analysis revealed a similar pattern of age-of-acquisition effects on cortical thickness (Table 2). Age of acquisition and cortical thickness were positively correlated in left IFG in the bilingual subjects (Fig. 2a); the later an L2 was acquired after an individual had gained proficiency in an L1, the thicker the cortex. A significant negative correlation with age of acquisition was also seen in the right IFG for the bilingual subjects (Fig. 2b); the later they learned an L2, the thinner the right frontal cortex. The only other region to show a significant correlation with age of acquisition of L2 was the left superior parietal lobe, where cortical thickness increased the later the L2 was acquired (Fig. 3).

4. Discussion

Our study of monolingual and bilingual subjects shows that acquisition of two languages relative to one language has no additional effect on brain development when acquisition is simultaneous. However, learning a second language after gaining proficiency in the first ("native") language modifies the brain's structure. Furthermore, the later in childhood the second language is acquired, the greater the thickness of the left inferior frontal cortex and the thinner the right.

In this study we investigated whether age of acquisition, subjective proficiency levels, and length of experience with an L2 correlate with anatomical characteristics. In our analyses, only the age of L2 acquisition analysis was significant. The different directions of the relationship between age of acquisition and cortical thickness in the left and right IFG are consistent with the different patterns of functional lateralization that have been reported in studies of bilingual adults (Hull & Vaid, 2007). In the latter study they report that bilinguals who acquired both languages by six years of age show involvement of both hemispheres in both languages, whereas those who acquired their second language after age six show left hemisphere dominance for both languages. They also found that the less proficient an individual is in the second language acquired late, the more leftwards the lateralization of function.

Grey matter density in different portions of the parietal cortex has been linked in previous studies to age of acquisition of L2 (left hemisphere; Mechelli et al., 2004), vocabulary size in adolescents (bilateral areas; Lee et al., 2007; left hemisphere; Richardson, Thomas, Filippi, Harth, & Price, 2010), and to the number of non-native languages (and most likely words) spoken by multilinguals (right hemisphere; Grogan et al., 2012). The structural changes in this region are described as reflecting an explicit learning strategy for

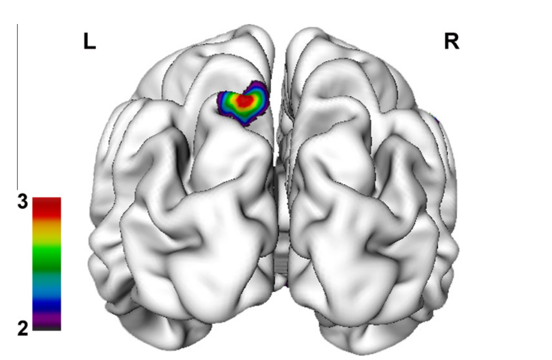

Fig. 3. Regression of cortical thickness and age of L2 acquisition (AoA) within the bilingual group ($n = 66$). Results from the statistical analysis of data are displayed on the surface of a standardized brain in terms of statistical color map. See Table 2 for a summary of significant results; the peak was significant after FDR correction at $q = 0.05$.

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linking new words to concepts (e.g. Richardson et al., 2010), a process that is implicit when learning languages natively (from infancy). The changes in inferior frontal and parietal cortex in our study of cortical thickness might similarly reflect different learning processes associated with native (presumed implicit) and acquired (presumed explicit) language learning, but more work is needed to tease apart the differential contribution of these different brain regions.

Thicker cortex associated with later acquisition of L2, as in the early, and also in the late sequential bilingual groups, may reflect the idea that acquiring an L2 as a new skill after infancy induces specific structural changes in brain areas demanded by the task, namely in the left inferior frontal and superior parietal regions, stimulating new neural growth and connections as seen in the acquisition of other complex motor skills such as juggling (Draganski et al., 2004; Scholz, Klein, Behrens, & Johansen-Berg, 2009). Another possibility is that this result may be attributed to age variations (ranging from 18 to 48 in the study), since recent data (Lemaitre et al., 2012) has revealed more marked reductions of cortical thickness associated with age in the left inferior frontal gyrus. However, this interpretation is unlikely because we included chronological age as a covariate. It is also unlikely that any differences in gender ratios across the groups are contributing to our findings as the ratio of females to males was similar for simultaneous and the late bilingual groups, between which the most important group differences were observed.

Whereas evidence garnered from behavioral and functional imaging laterality studies is inferential and cannot directly point to underlying neural mechanisms, our findings indicate that at a structural level, the effects of language learning differ between simultaneous and successive bilinguals, and may underpin the difficulties some late learners experience with L2 mastery. Simultaneous acquisition of two languages and early bilingualism are the conditions associated with greatest proficiency and show the smallest effect on brain structure relative to monolingualism. Our results provide structural evidence that age of acquisition is crucial in laying down the structure for language learning. The greater differences in brain structure associated with later sequential L2 acquisition might reflect recruitment of suboptimal neural circuits for language learning. Future studies would need to explore how these age-of-acquisition cortical thickness effects relate to proficiency in L2 as in the present study we did not have sufficient measures of proficiency to explore these possibilities in more depth.

Acknowledgments

This work was supported by a grant from the Natural Science and Engineering Research Council of Canada to Denise Klein and from an Oxford McGill Neuroscience Collaboration Pilot project awarded to Watkins, Gracco and Klein.

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