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Functional magnetic resonance imaging study of Piaget's conservation-of-number task in preschool and school-age children: A neo-Piagetian approach

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ABSTRACT

Jean Piaget's theory is a central reference point in the study of logico-mathematical development in children. One of the most famous Piagetian tasks is number conservation. Failures and successes in this task reveal two fundamental stages in children's thinking and judgment, shifting at approximately 7 years of age from visuospatial intuition to number conservation. In the current study, preschool children (nonconservers, 5–6 years of age) and school-age children (conservers, 9–10 years of age) were presented with Piaget's conservation-of-number task and monitored by functional magnetic resonance imaging (fMRI). The cognitive change allowing children to access conservation was shown to be related to the neural contribution of a bilateral parietofrontal network involved in numerical and executive functions. These fMRI results highlight how the behavioral and cognitive stages Piaget formulated during the 20th century manifest in the brain with age.

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Introduction

Psychological research regarding numerical abilities in children proliferated during the second half of the 20th century, yielding evidence of precocious skills in preschool children and even babies (Berger, Tzur, & Posner, 2006; Lipton & Spelke, 2003; McCrink & Wynn, 2004; Mehler & Bever, 1967; Wynn, 1992; Wynn, 1998). Despite these precocious skills, however, children under approximately 7 years of age fail to solve the famous Piaget's conservation-of-number task (Piaget, 1941/1952; see also Markovits & Barrouillet, 2004, for other examples of such contradictions in the field of reasoning stages). This developmental evidence is quite robust and manifests in today's preschoolers half a century after Piaget's discovery (Houdé, 1997; Ping & Goldin-Meadow, 2008). The conservation-of-number task consists of the presentation of two rows containing the same number of objects placed in one-to-one correspondence (Fig. 1). Children are asked whether the two rows contain the same number of objects. Once the children acknowledge this equality, one of the rows is transformed in length but not in number (i.e., the objects in the row are spread apart [Fig. 1]). Children are again asked

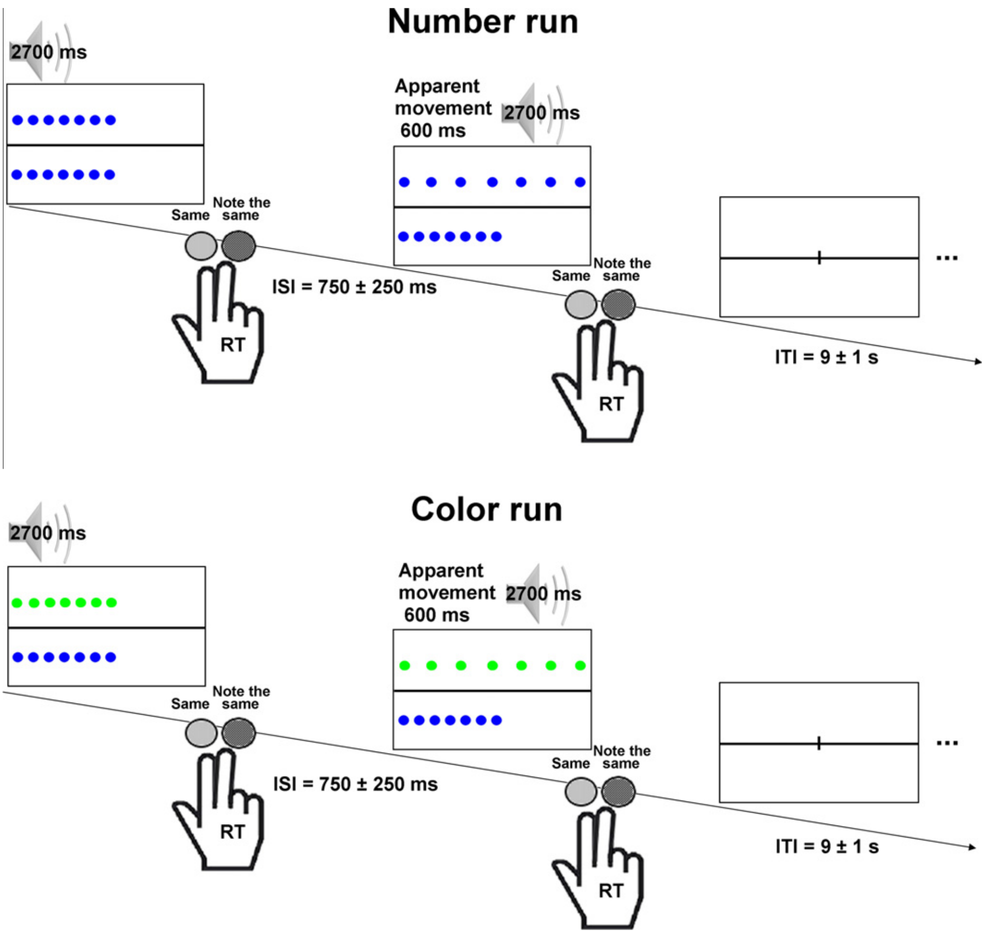

Fig. 1. Sequence time of conservation-of-number task (Number run) and control task (Color run). Note that the fixation period (duration = 9 s, *SD* = 1) was used as a resting condition. ISI, interstimulus interval; RT, reaction time; ITI, intertrial interval.

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whether the two rows contain the same number of objects. Until approximately 7 years of age, children are considered as ''nonconservers'' because they erroneously state that there are more objects in the longer row. However, after 7 or 8 years of age, children are designated as ''conservers'' because they correctly state that the numbers of objects in the two rows are equal. According to Piaget's theory (Piaget, 1941/1952, 1984), total success in this task proves the solidity of the number concept and delineates an important step in the acquisition of concrete logico-mathematical skills in children.

Piaget's interpretation was that conservers correctly perform the conservation-of-number task because they understand the equivalency of numerical quantities and use a cognitive reversibility operation, which is the ability to see visuospatial transformation and then mentally reverse it so that the perceptual change is cancelled out. Consequently, regardless of apparent transformations such as when the objects in a row are spread apart, conservers correctly indicate that the two rows still contain the same numbers of objects. On the other hand, the youngest children (i.e., the nonconservers) are fundamentally intuitive and limited to a perceptual way of processing information, which is based on the visuospatial property of length in this example (Piaget, 1941/1952). Consequently, even if the children correctly indicate that the numbers of objects are initially the same, they change their judgment after the objects are moved. Because of the use of a misleading visuospatial ''length-equals-number'' strategy, the children erroneously indicate that the longer row contains more objects. Neo-Piagetian authors have also claimed that young children are incapable of inhibiting the inappropriate length-equals-number heuristic, leading to a failure in grasping the number principle per se (Bjorklund & Harnishfeger, 1990; Dempster & Brainerd, 1995; Houdé, 1997; Houdé, 2000; Houdé & Guichart, 2001). In addition, even adults must inhibit this visuospatial heuristic to perform a Piaget-like number conservation task correctly (Daurignac, Houdé, & Jouvent, 2006; Joliot et al., 2009; Leroux et al., 2006; Leroux et al., 2009).

Many developmental studies in the field since the mid-20th century have reported these two stages at the behavioral level during different classical Piagetian tasks based on number, liquid volume, matter quantity, weight, or length (Houdé, 1997; Piaget, 1941/1952, 1984; Ping & Goldin-Meadow, 2008; Poirel et al., 2011; Sugarman, 1987; Zhang et al., 2008). Even if transitional age could vary according to the material presented (i.e., ''horizontal decalages'' following Piaget's terminology), the aforementioned two steps of development were evidenced between younger and older children. Hereafter, we focus only on the conservation-of-number task. Despite a few electrophysiological attempts with analogue tasks (Stauder, Molenaar, & van der Molen, 1999; Zhang et al., 2008), the brain network allowing children to succeed in this task has never been investigated using functional magnetic resonance imaging (fMRI). The current work aimed to uncover the neural network that allows only conservers to perform the task with total success—that is, success both before and after relocation of the objects (Fig. 1)—by accurately applying the initial equality judgment and then the conservation judgment.

We used fMRI to test this famous two-stage pattern of logico-mathematical performance in an experimental paradigm where 5- and 6-year-olds (presumed nonconservers) and 9- and 10-year-olds (presumed conservers) completed two experimental tasks. A computer version of the classical Piaget's conservation-of-number task was elaborated to investigate the neural network that allows children to surpass the inappropriate length-equals-number heuristic (Fig. 1, top). A control task similar to the first one was also proposed to discriminate between general default mode brain maturity during development and differences in cerebral activation between younger and older children induced by a successful Piagetian task. A recent study revealed that the default neurocognitive brain functioning strongly evolves with age (Dosenbach et al., 2010). Thus, it was necessary to evaluate whether the differences found between the two age groups of children were actually due to solving the experimental task or to a more global evolution of general brain activity between 5–6 and 9–10 years of age. For the control, we used a qualitative judgment task with the same experimental procedure and stimuli as the Piagetian number task in which children needed to indicate whether the two rows of objects presented the same color (Fig. 1, bottom). If differences in brain activation between the older and younger children actually reflected the capacity specifically to solve the Piagetian conservation-of-number task, then these differences would not be observed in the control task. Because our younger group of children was near the transitional age of success with the task, we also identified children in this age group who showed a tendency to succeed in the task for further analysis. By minimizing any confounding effect of age, this comparison between the successful children and those of the same age

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group who failed to solve the task was performed to reveal the brain network typically responsible for the emergence of conservation ability.

Based on our previous results in adults (Leroux et al., 2006; Leroux et al., 2009), we hypothesized that an understanding of the reversibility principle in children might be concomitant with the development of an executive brain network. It is now well accepted that executive functions originate from a dynamic frontal cortical network (see Ball et al., 2011). Thus, activation would be evidenced in frontal regions in older children—and even in younger children who have begun to perform the task correctly—but not in younger children who failed at the task. We also hypothesized that this brain network would include the inferior frontal cortex, known to be involved in executive working memory (McNab et al., 2008; Todd, Han, Harrison, & Marois, in press), which would be necessary here to inhibit visuospatial cues (Houdé, 2000) by using and maintaining the cognitive reversibility operation.

Method

Participants

A total of 60 children recruited from preschools and schools in Caen (Calvados, France) participated in this study: 38 5- and 6-year-olds and 22 9- and 10-year-olds. The children had no trouble regarding reading and mathematical acquisition, no psychological or psychomotor therapies (only 1 child in each age group was under light speech therapy), and no history of neurological disease. The T1-weighted MRI indicated that no children had any cerebral abnormalities. The local ethics committee approved the study. Written consent was obtained from the parents and the children themselves after detailed discussion and explanation (individual consent for children was adapted as a ‘‘smiley’’ associated with a specific color).

MRI familiarization at school

To help the children feel confident with the experimenters and experimental material, they participated individually in an half-hour-long familiarization session at school the day before the MRI in the laboratory. The session consisted of a ‘‘statue game’’ in which they needed to stay as still as a statue in a toy tunnel imitating the MRI scanner and its technological environment, including the recorded noises of all MRI sequences, cardboard head coil, medical tape on the forehead, and response pad (with practice trials) (Figs. 2A and B). The day of the MRI in the lab, the same familiarization process was repeated just prior to the experiment.

fMRI imaging protocol

Images were acquired using a 3T MRI scanner (Achieva, Philips Medical System, Netherlands) (Fig. 2C). In a first anatomical session, three-dimensional (3D) T1-weighted spoiled gradient images (field of view [FOV] = 256 mm, slice thickness = 1.33 mm, 128 slices, matrix size = 192 × 192 voxels, and duration = 5 min 7 s) were acquired while the children passively watched a cartoon on an MRI-compatible screen. The sedative effect of audio/visual systems on children in MRI scanners has been demonstrated; it reduces motion, provides a positive experience, and decreases wait times (Lemaire, Moran, & Swan, 2009). After a break outside the scanner, the fMRI session, consisting of two different runs, was conducted with $T2^*$-weighted, gradient echo planar images acquired with a repetition time of 2 s, an echo time of 35 ms, and a flip angle of 80° for 31 axial slices, 3.5 mm thick, with a 224-mm FOV and a 64 × 64 grid (210 volumes in 7 min for each run). Additional anatomical $T2^*$-weighted images were acquired with 60 slices, 2.3 mm thick, and a 112 × 112 grid (2 min 10 s duration) to facilitate realignment between T1 and echo planar images.

Throughout this second MRI session, children performed two different runs: Piaget’s conservation-of-number task (called the Number task) first and then the control task (called the Color task). Although this may be a limitation of the current study, we decided to adhere to the classical Piagetian design (in which no control task was used). This meant always presenting the control task at the end

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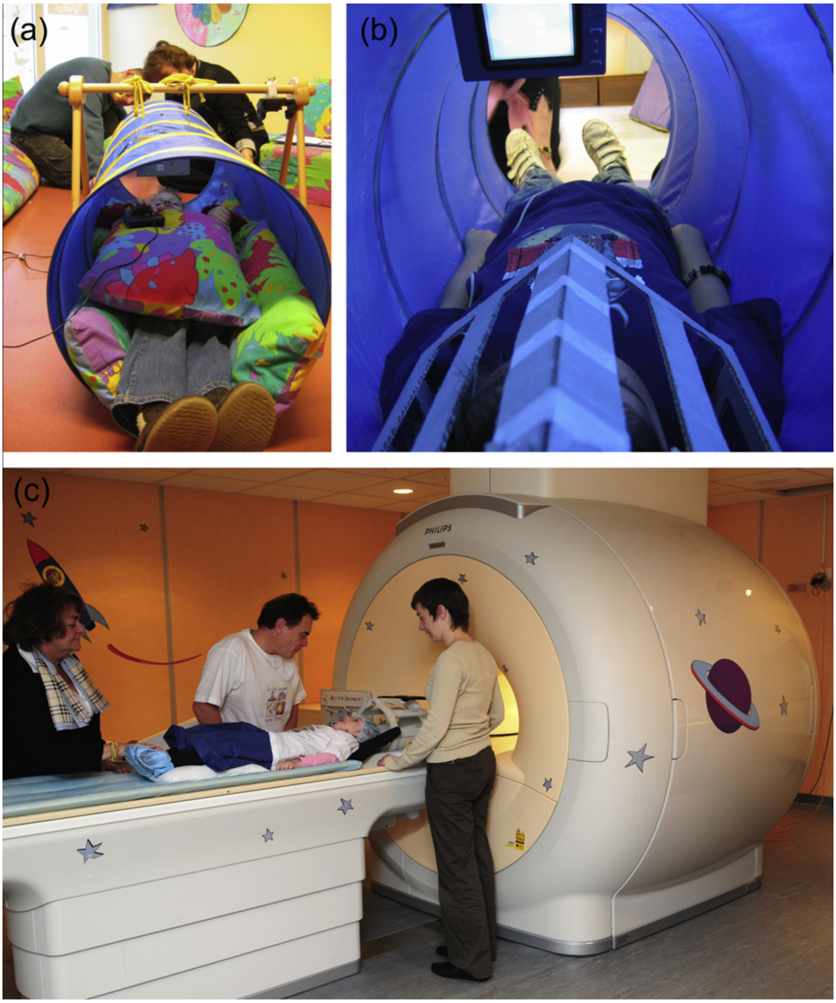

Fig. 2. Photographs of the experimental environment. (A) Training procedure at the school. (B) Inside the toy tunnel, a child wearing the cardboard head coil and looking at the screen while playing the "statue game." (C) Preparation of a 5-year-old in the MRI scanner with a child-friendly environment.

of the functional session. Such a precaution is important because it avoids any control task priming and/or interference effects on the children's judgments during the conservation-of-number task.

During the Number task, the children were presented with conservation trials. Each trial consisted of two rows, each containing the same number of objects (5, 6, or 7). According to the conservation principle, the number of objects was always the same in both rows. Hence, even though the number of objects (5, 6, or 7) varied across trials, all conservation trials, by definition, involved the same correct response (i.e., numerical equivalence), leading to a possible habituation effect as the fMRI experiment progressed. To minimize this potential bias inherent in Piaget's conservation design, the experimenter told the children before the functional session that they needed to pay close attention because there might be traps in the task. For each trial, children were asked to judge the numerical equivalence of two rows of objects when the rows had the same length (Fig. 1). After a jittered interstimulus interval of 750 ± 250 ms, the objects in one of the rows were spread apart by apparent movement on the computer screen. After the objects in one of the two rows had been moved, the children were again instructed to judge the numerical equivalence of the two rows of objects when their

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length, but not their number, differed. Children responded by pressing the "same" button or the "not the same" button of the response box. The question "Is the number of objects the same in both rows?" was verbally delivered for each trial (2.7 s duration each), and each trial remained present on the screen until the children responded.

Children were then presented with the Color task, in which they needed to make a qualitative decision about the two rows of objects. Children were presented with the same experimental stimuli as during the Number task except that the two rows consisted of either the same colors or different colors (Fig. 1, bottom). Same and different trials were presented randomly. Children were asked, "Are the objects in both rows the same color?" and responded by pressing the "same" button or the "not the same" button on the response box.

Children used their preferred hand to give their answers with the response pad. During both tasks, the children were instructed to look passively at a line on the screen between each experimental trial, defining a control rest condition. The inter-trial interval was jittered and lasted 9 s, standard deviation (SD) = 1.

Data analysis

Of the original group of 60 children, 16 5- and 6-year-olds (mean age = 5.9 years, SD = 0.7, range = 5.2–7.2, 6 boys and 10 girls, 12 right-handed) and 16 9- and 10-year-olds (mean age = 10.2 years, SD = 0.6, range = 9.2–10.9, 8 boys and 8 girls, 11 right-handed) were included in the data analysis as nonconservers and conservers, respectively. Among the other children, 21 were excluded because of excessive motion in the MRI scanner (i.e., >3 mm in translation or >3° in rotation). A further 7 children (5–6 years of age) exhibited a transitional pattern of performance, and their data were used in a complementary analysis (see "Complementary Analysis" section below).

Preprocessing and statistical analysis, as described in detail elsewhere (Leroux et al., 2006; Leroux et al., 2009), were carried out using SPM5 (statistical parametric mapping) software (Wellcome Department of Cognitive Neurology, www.fil.ion.ucl.ac.uk/spm). Preprocessing included slice–time correction, motion correction, visually checking the realignment of the mean echo planar image with the first one on the T1 image, normalization using the Montreal National Institute (MNI) template, and spatial smoothing with a 6-mm Gaussian kernel. Comparisons of interest were implemented using a general linear model with the standard adult hemodynamic response function because no differences have been reported for children (Kang, Burgund, Lugar, Petersen, & Schlaggar, 2003), convolved with trial onsets, the end of the second response time as an offset, and six motion parameters (x, y, and z axes for translation and rotation) as factors of noninterest.

Data were included in a multiple-participant fixed-effect analysis to determine significant differences between each group for the Number and Color tasks. This method is often adapted for studies involving small groups of participants, as is usually the case for neuroimaging studies in children (see Dehaene-Lambertz et al., 2010). Moreover, the fMRI design of the current experiment did not allow separate analyses between the first phase and the second phase of each trial (i.e., before and after the object displacement [see Fig. 1]). The use of fixed-effect analyses allowed compensating for this methodological concern by improving statistical sensibility. Activations were reported when voxels were significant at $p < .001$ family-wise error (see Storey, 2002) for group effects, with a minimum extent of 10 voxels in clusters (i.e., brain areas activated in each group of children), and at $p < .01$ false discovery rate for group differences, with a minimum extent of 50 voxels in clusters (i.e., for each task, 9- and 10-year-olds *minus* 5- and 6-year-olds contrast, with an inclusive mask of 5- and 6-year-olds, and another analysis with the reverse comparison and an inclusive mask of 9- and 10-year-olds).

Results

Behavioral results

During the Number task, children from both age groups were highly accurate in identifying the numerical equivalence when the rows were the same length (percentage correct responses: 99.5

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and 99.7% for 5–6- and 9–10-year groups, respectively). As expected, 9- and 10-year-olds succeeded again after the objects in one of the rows were moved apart (percentage correct responses: 2.5% and 99.7% for nonconservers [5- and 6-year-olds] and conservers [9- and 10-year-olds], respectively). Response times were not significantly different between groups for either task (rows same length: 940 vs. 1130 ms for 5–6- and 9–10-year groups, respectively, $t(30) = 0.66$, $p = .75$, effect size = 0.24; objects in one row moved: 641 vs. 710 ms for 5–6- and 9–10-year groups, respectively, $t(30) = 0.55$, $p = .71$, effect size = 0.20). Similarly, no group difference was found regarding the number of trials performed (21 trials, $SD = 3$, for 5–6-year group, and 21 trials, $SD = 2$, for 9–10-year group, $t(30) = 0.15$, $p = .88$, effect size = 0.04).

During the Color task, the 9- and 10-year-old conservers were significantly faster than the 5- and 6-year-old nonconservers (rows the same length: 1165 vs. 545 ms for 5–6- and 9–10-year groups, respectively, $t(30) = 3.98$, $p = .0003$, effect size = 0.99; objects in one row moved: 989 vs. 526 ms for 5–6- and 9–10-year groups, respectively, $t(30) = 2.33$, $p = .02$, effect size = 0.85), inducing a slightly significant increase in the number of trials performed (21 trials, $SD = 2$, for 5–6-year group, and 23 trials, $SD = 2$, for 9–10-year group, $t(30) = 2.04$, $p = .05$, effect size = 0.72). However, both groups of children responded accurately without significant differences between the groups (99.2 vs. 99.4%, $t(30) = 1.79$, $p = .66$, effect size = 0.59, with both rows the same length, 97.5 vs. 96.7%, $t(30) = 1.46$, $p = .16$, effect size = 0.60, when the objects in one row were moved).

After the MRI session, all children were presented again with the same classical conservation-of-number task in a quiet room using noncomputerized materials. The results confirmed that all 5- and 6-year-olds identified as nonconservers still showed a similar performance on the task and that all 9- and 10-year-olds were conservers. The 7 young conservers who exhibited a transitional pattern of performance were not as stable in their judgments and showed only an emerging tendency to succeed in the task (i.e., shifting back and forth between correct and erroneous responses, as already reported by Piaget and collaborators in their seminal work [see Piaget, 1941/1952]). Note that all nonconserver children indicated wrongly (just after the MRI session) that there were more objects because the row was longer.

fMRI

The fMRI data were analyzed twice as follows: (a) for the group effect, revealing the brain areas most activated for each group during both tasks (Number and Color) compared with the control resting condition, and (b) with contrast analyses, revealing the differences in brain activation between the two groups for both tasks.

The group analyses showed that during the Number task, a bilateral posterior network that included primary (calcarine) and associative areas of the ventral and dorsal pathways was activated in both groups of children. The visual areas of the ventral pathway were extended as far as V4 (the bilateral lingual, fusiform, middle, and inferior occipital gyri). The right occipito-temporal junction (the posterior part of the middle and inferior temporal gyri) was also activated. The areas in the dorsal pathway included the superior and middle occipital gyri with an internal activation of the precuneus. Both groups also exhibited activation in a set of bilateral primary and associative areas in the motor and auditory cortices, including the precentral and postcentral gyri, the supplementary motor area, the cerebellum, and the cortices surrounding Heschl's gyrus. In addition, a set of parietal and frontal areas was activated, including the bilateral intraparietal sulcus (IPS) and the bilateral frontal gyri, and there was left and bilateral activity in the cingulate, insula, and thalamus (Table 1 and Fig. 3).

Regarding the Color task (Fig. 3), group analyses revealed that for the 5- and 6-year-old nonconservers, the significant clusters were located in the cortices surrounding the bilateral superior and middle temporal gyri, Heschl's gyrus, and calcarine sulcus. Bilateral activations were also found in the precentral gyrus, supplementary motor area, supramarginal gyrus, cingulate, and insula. Activation was seen in the right hemisphere in the inferior parietal gyrus, angular gyrus, and middle and inferior frontal gyri. Concerning the 9- and 10-year-old conservers, significant clusters were located in the same areas, but to a larger extent, including additional bilateral activation of the parietal and angular gyri.

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Table 1
Anatomical localizations, extent of activation, MNI coordinates, and *Z* scores for maximal activation in both age groups for the Number and Color tasks.

Anatomical localization	Number of voxels	Hemisphere	MNI coordinates			*Z* score
			X	*Y*	*Z*	
Unsuccessful 5- and 6-year-olds						
Middle occipital gyrus	132	L	−28	−78	16	6.89
Middle and inferior occipital gyri	137	L	−44	−76	2	6.77
Superior, middle, and inferior temporal gyri	13000	R	56	−10	6	>8
Lingual gyrus		L & R				
Superior and inferior parietal gyri		R				
Calcarine and fusiform gyri		L & R				
Superior, middle, and inferior occipital gyri		L & R				
Heschl's gyrus		R				
Cerebellum 6 and crus_1		L & R				
Superior and middle temporal gyri	7955	L	−50	−18	6	>8
Precentral and postcentral gyri		L				
Supramarginal gyrus		L				
Inferior parietal gyrus		L				
Rolandic operculum		L				
Superior temporal gyrus, pole		L				
Heschl's gyrus		L				
Insula		L				
Superior and inferior parietal gyri	253	L	−22	−60	50	>8
Precentral gyrus	574	R	48	0	56	>8
Supplementary motor area	2515	L & R	0	−2	58	>8
Middle and posterior parts of the cingulate	75	L & R	2	−30	28	7.25
Middle frontal gyrus	609	R	44	44	20	>8
	129	L	−44	40	24	7.08
	13	L	−34	46	34	6.02
Insula	18	L	−32	16	6	5.99
Thalamus	73	L	−12	−18	12	7.23
Caudate nucleus	11	L	−10	−2	14	5.98
Successful 9- and 10-year-olds						
Calcarine, fusiform, and lingual gyri	70644	L & R	30	−56	50	>8
Superior, middle, and inferior occipital gyri		L & R				
Cuneus and precuneus gyri		L & R				
Superior and middle temporal gyri		L & R				
Superior and inferior parietal gyri		L & R				
Precentral and postcentral gyri		L & R				
Supplementary motor area		L & R				
Supramarginal and angular gyri		L & R				
Superior, middle, and inferior frontal gyri		L & R				
Cingulate gyrus		L & R				
Insula		L & R				
Thalamus		L & R				
Middle temporal gyrus, pole	12	L	−56	8	−36	6.16
Postcentral gyrus	19	L	−64	−18	36	6.62
Superior frontal gyrus	24	R	18	66	14	6.14
Middle frontal gyrus, orbital part	325	L	−46	54	−10	>8

Note. L, left; R, right.

The contrast analysis between the two age groups for the Number task revealed larger activation in regions located in the bilateral ventral and dorsal visual pathways and a bilateral parietofrontal network in conservers (Table 2, top, and Fig. 4). Posterior activation was identified in the calcarine sulcus and lingual, inferior occipital, and temporal gyri for the ventral pathway and in the cuneus and superior and middle occipital gyri for the dorsal pathway. The bilateral parietofrontal network included the IPS, angular gyrus, insula/orbital part of the inferior frontal gyrus, and middle frontal gyrus with the orbital/opercular parts of the right middle frontal gyrus (Fig. 4). The left precentral and bilateral cerebellum were also found to be more activated in the 9- and 10-year-olds than in the 5- and 6-year-olds.

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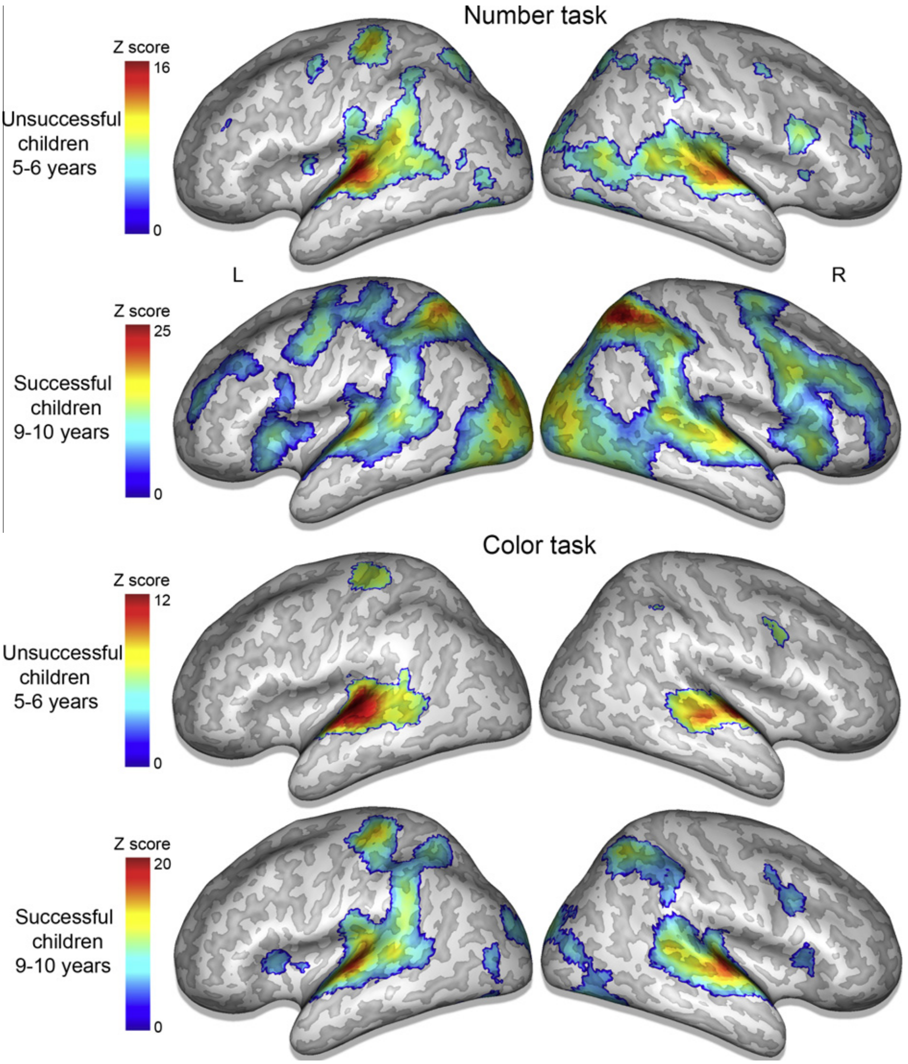

Fig. 3. 3D rendering of areas activated in 5–6- and 9–10-year groups (nonconservers and conservers, respectively) during the Number task and control Color task. L, left; R, right.

The opposite comparison concerning the two age groups revealed two foci along the sylvian sulcus, including Heschl's gyrus with its surrounding cortex, the left precentral gyrus, the bilateral supplementary motor area, the left supramarginal gyrus, and the right middle temporal gyrus (Table 2, middle). Finally, the contrast analysis between the 9–10- and 5–6-year groups for the Color task failed to reveal significant activation. The opposite comparison showed activation in the bilateral (superior) temporal cortices that was more extensive in the right hemisphere and in the bilateral precuneus, bilateral thalamus, right supplementary motor area, and left caudate.

Complementary analysis

Note that some 5- and 6-year-olds showed a tendency to succeed at the task ($n = 7$, mean age = 6.7 years, $SD = 0.4$, 1 boy and 6 girls, 6 right-handed) (percentage correct responses: 98%

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Table 2
Anatomical localizations, extent of activation, MNI coordinates, and *Z* scores for maximal activation in the between-group comparisons.

Anatomical localization	Number of voxels	Hemisphere	MNI coordinates			*Z* score
			X	*Y*	*Z*	
Successful 9- and 10-year-olds minus unsuccessful 5- and 6-year-olds						
Calcarine	6556	L & R	30	−56	50	>8
Lingual gyrus		L & R				
Superior, middle, and inferior occipital gyri		L & R				
Cuneus		L & R				
Intraparietal sulcus		R				
Angular gyrus		R				
Cerebellum 6		L & R				
Temporal poles of the superior and inferior temporal gyri	58	R	48	22	−36	4.10
Intraparietal sulcus	611	L	−38	−56	56	6.21
Precentral gyrus	109	L	−48	−8	58	4.98
Middle frontal gyrus	681	R	50	22	38	6.07
	95	L	−36	34	40	4.36
Middle frontal gyrus, orbital part	103	R	42	46	−14	4.95
	158	R	44	58	0	4.44
Insula/inferior frontal gyrus, orbital part	186	R	36	22	−10	4.88
	59	L	−32	20	−14	4.47
Unsuccessful 5- and 6-year-olds minus successful 9- and 10-year-olds						
Rolandic operculum, superior temporal, supramarginal, postcentral, insula, and Heschl's gyrus	1504	R	54	−6	6	>8
Rolandic operculum, superior temporal, supramarginal, postcentral, insula, and Heschl's gyrus	1170	L	−56	−6	4	7.29
Supramarginal gyrus	52	L	−62	−26	44	4.87
Precentral gyrus	86	L	−34	−26	62	4.81
	87	R	42	−18	66	5.44
Supplementary motor area	56	L & R	2	−6	54	4.44
Middle temporal gyrus	50	R	44	−62	14	4.66
Successful 5- and 6-year-olds minus unsuccessful 5- and 6-year-olds						
Middle occipital gyrus	134	L	−30	−76	34	5.45
Precentral gyrus	300	R	30	−14	52	5.18
Superior and inferior parietal gyri	939	R	24	−54	42	5.51
Inferior parietal gyrus	99	L	−40	−48	48	3.98
Middle frontal gyrus	614	R	34	28	32	5.83
	68	R	30	50	22	4.05
	76	L	−28	26	34	4.31
Superior and middle frontal gyri, orbital parts	124	R	26	56	−8	5.00

Note. L, left; R, right.

when the rows were of the same length and 71% after the objects in one of the rows had been spread apart). Behavioral and fMRI results for these children were compared with those from a subgroup of 7 children randomly selected from the 16 previous 5- and 6-year-olds who failed to correctly solve the task (i.e., the nonconservers). The subgroup was simply matched on gender (1 boy and 6 girls) and handedness (6 right-handed). Response times did not differ significantly between the two groups of children (1596 ms, *SD* = 1697, for successful 5- and 6-year-olds, and 619 ms, *SD* = 157, for unsuccessful 5- and 6-year-olds, *t*(12) = 1.51, *p* = .18, effect size = 0.81), but the successful 5–6-year group performed a smaller number of trials (18, *SD* = 4) than the unsuccessful 5–6-year group (22, *SD* = 4), *t*(12) = 2.30, *p* = .02, effect size = 0.99. The fMRI contrast analysis revealed differences comparable to those found for unsuccessful 5- and 6-year-olds versus 9- and 10-year-olds. In particular, the successful 5–6-year group presented larger activations than the unsuccessful 5–6-year group in a parietofrontal network that included the IPS and the middle frontal gyrus (see Table 2, bottom, and Fig. 5).

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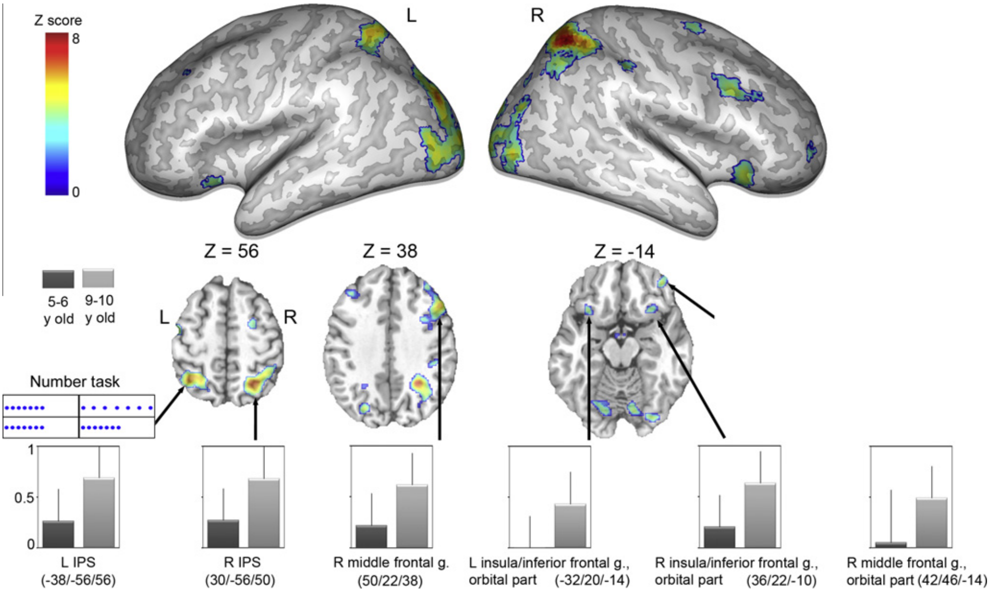

Fig. 4. 3D rendering of areas activated more in successful 9- and 10-year-olds (conservers) compared with unsuccessful 5- and 6-year-olds (nonconservers) during the Number task. Each plot represents the mean bold signal in the pointed cluster. L, left; R, right; frontal g., frontal gyrus.

Discussion

During many everyday situations, numerosity and length are strongly linked; usually, more objects occupy more space. Piaget used this relationship in his conservation-of-number task, which aimed to test the solidity of the number concept in children. Despite probably having precocious numerical abilities as early as 5 months of age (e.g., McCrink & Wynn, 2004; Wynn, 1992; Wynn, 1998), children under 7 years of age erroneously think that the longer row contains more objects when presented with two rows of different lengths but containing the same number of objects. Although many behavioral studies that reiterate this developmental finding have been conducted, the precise cerebral bases allowing older children (over 7 or 8 years of age) to succeed in Piaget's conservation-of-number task had not been investigated with fMRI. In the current fMRI study, children from both age groups successfully identified the numerical equivalence when the rows were the same length, but only 9- and 10-year-olds succeeded consistently after the objects in one of the rows had been moved apart. These behavioral results confirmed those obtained by Piaget (1941/1952, 1984; see also Sugarman, 1987) and all neo-Piagetian authors (see Houdé, 2000, for a review). Thus, the older children were conservers in the Piagetian sense; that is, they had reached the developmental conservation-of-number stage.

Brain areas activated in both younger and older children

In both groups of children in the initial analysis, the identification and visual discrimination of the two rows of objects arose during both tasks from activity in ventral pathway areas (see Goesaert & Op de Beeck, 2010) and by activation of the occipito-temporal junction in the right hemisphere, known to be involved in the visual discrimination of forms spatially presented (Vidnyánszky, Gulyás, & Roland, 2000). The areas of the dorsal pathway observed only for the Number task are known to be involved in sustaining visuospatial information processing (Haxby et al., 1991), corresponding here to the children's dual exploration of the computer screen (i.e., quantitative screening), which a horizontal line divided into two spaces.

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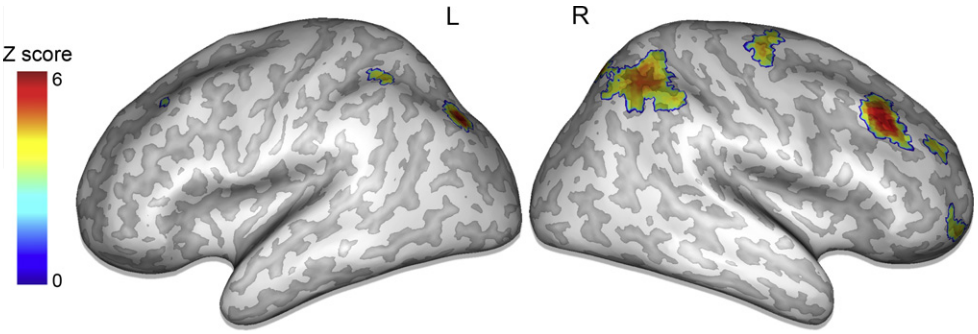

Fig. 5. 3D rendering of areas activated more in successful 5- and 6-year-olds (who showed a tendency to correctly respond) compared with unsuccessful 5- and 6-year-olds during the Number task. L, left; R, right.

During the Piagetian task, number comparison led to activation of the IPS in both groups of children. Of importance, this finding of a numerosity brain area (Dormal & Pesenti, 2009) indicated that both groups of children actually processed the Piagetian task as a quantitative number task. Of further interest, despite the involvement of the IPS in all children, the younger ones failed to correctly conserve the number dimension after the displacement, suggesting that some other regions are necessary to surpass the perceptual bias of length. The spatial working memory component required for the numerical comparison has been suggested here by the frontal superior and middle area involvement (Owen, 1997). Finally, the activation of the insula and frontal gyrus likely reflects a kind of episodic memory retrieval (Herrmann et al., 2001), that is, the retrieval of visuospatial configurations (the repeated row displays) during task monitoring.

Brain areas activated in children who succeeded at the Piagetian task

The contrast between the successful group of older children (conservers) and the unsuccessful younger children (nonconservers), but also the comparison between the groups of younger children who tended to succeed or who failed at the task, highlighted the brain areas necessary for succeeding in Piaget's conservation-of-number task. Even though the IPS was conjointly activated during the task in all groups, this region was more activated in the successful groups. It suggests that success in Piaget's conservation-of-number task requires a more important involvement of parietal regions, conjointly activated with the prefrontal lobe, to form a working memory network. This network is known to be involved for comparing different possible and competitive task responses (Deary, Penke, & Johnson, 2010). The finding is also in agreement with the view that bilateral IPS activation is classically related to numerical cognition in adults and children (Ansari & Dhital, 2006; Kawashima et al., 2004; Piazza & Dehaene, 2004). Of interest, Dormal and Pesenti (2009) recently showed that numerosity and length processing conjointly recruit the right IPS, supporting the view that both left and (even more) right parietal regions are activated during conceptual decisions about numbers (Cappelletti, Lee, Freeman, & Price, 2010). As claimed by Fuster (2003), solving a Piaget's task such as the conservation-of-number task "undoubtedly engages the circuitry between areas of sensory association and the premotor cortex as well as between higher polysensory and prefrontal areas" (pp. 218–219). Enhanced prefrontal areas are needed to perform this Piaget task successfully (i.e., before and after objects are moved), as shown primarily by the activation of the bilateral inferior frontal gyri in successful children.

The inferior frontal gyrus is usually related to inhibitory control in working memory (Aron, Robbins, & Poldrack, 2004; Konishi et al., 1998; McNab et al., 2008) and known to be involved in both cognitive control (Fuster, 2003; Miller, 2000) and number processing when conjointly activated with the IPS (Cappelletti et al., 2010; Dormal & Pesenti, 2009; Piazza & Dehaene, 2004). In agreement with the hypothesis that the frontal lobe is the substrate for many higher cognitive functions (Fuster, 2003)

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such as inhibitory control during response interference tasks, this inferior frontal activation could reflect the monitoring of perceptual (visuospatial) conflict between length and number responses in Piaget's conservation task (Bjorklund & Harnishfeger, 1990; Dempster & Brainerd, 1995; Houdé, 2000; Houdé & Guichart, 2001; Joliot et al., 2009; Leroux et al., 2006; Leroux et al., 2009). According to many neo-Piagetian authors such as Dempster and Brainerd (1995), "conservation and class inclusion have more to do with the ability to inhibit and resist interference than they do with the child's ability to grasp their underlying logic" (p. 15). The right parietofrontal network identified in the current study is also consistent with previous electrophysiological findings showing that conservers use the right hemisphere more than nonconservers when processing conservation tasks (McGlasson, 1995). Thus, the current results suggest that the developmental emergence of an additional parietofrontal network could facilitate the capacity of older children to surpass length interference during the conservation task and favor the number per se.

The executive control needed to resist the perceptual bias of length was also suggested by the involvement of the left insula. According to a recent meta-analysis of developmental fMRI studies in schoolchildren, the left insula is a core brain area specifically activated during executive function tasks, namely inhibition, response shifting, and working memory (Houdé, Rossi, Lubin, & Joliot, 2010). Consequently, appropriate inhibition of the length-equals-number response strategy in Piaget's conservation-of-number task (Houdé & Guichart, 2001) may depend on a large-scale executive brain network that includes the activation of the parietal and prefrontal areas conjointly with the insula. This interpretation is in agreement with the view that children may use their brains in ways that relate to achieving different levels of performance (Deary et al., 2010; Houdé, 2010).

The fact that the aforementioned network was not evidenced in the control task reduces the risk of a potential confounding by the general maturity of the functional network with age (Dosenbach et al., 2010) even if one could argue that different tasks can show different age-specific effects. Nevertheless, the data from the younger children who showed a tendency to correctly respond to the task suggest that succeeding at the conservation-of-number task rests on the observed parietofrontal network. Note also that brain activations found for the Piagetian task might merely reflect a basic sense of numerosity (rather than conservation abilities per se). Nevertheless, because both groups of children probably shared this sense of numerosity (in line with the precocious numerical abilities observed in young children [see Introduction]), the corresponding brain activations were theoretically canceled when we applied the subtraction method between conservers and nonconservers.

Finally, the opposite comparison—that is, the contrast between the unsuccessful younger group (nonconservers) and the successful older group (conservers)—was in agreement with the traditional view that nonconserver children base their judgment mostly on a perceptual way of processing (Houdé, 2000). The foci of activation around the auditory cortex probably indicate a higher perceptual field dependence of the verbally delivered question in young children, and the superior temporal activation may also reflect the visuospatial strategy used by the young children to solve the task (Karnath, 2001).

Conclusion

The results of this developmental fMRI study indicate that the involvement of an executive parietofrontal network may reflect the acquisition of number conservation skills by children. As has been proposed in neo-Piagetian theories (Bjorklund & Harnishfeger, 1990; Dempster & Brainerd, 1995; Houdé, 2000; Houdé & Guichart, 2001), children need executive function improvement to inhibit their erroneous intuitive perceptual responses and acquire the conservation principle. The current results corroborate this assumption by suggesting that the conservation-of-number acquisition rests on the neurocognitive development of a parietofrontal network.

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