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REPORT

Language-specific effects on number computation in toddlers

Célia Hodent,[1] Peter Bryant[2] and Olivier Houdé[1]

1. *UMR 6194, CNRS, CEA, Universities of Caen and Paris 5 (Sorbonne), Institute of Psychology, France*
2. *Department of Experimental Psychology, University of Oxford, UK*

Abstract

A fundamental question in developmental science is how brains with and without language compute numbers. Measuring young children's verbal reactions in France (Paris) and in England (Oxford), here we show that, although there is a general arithmetic ability for small numbers that is shared by monkeys and preverbal infants, the development of such initial knowledge in humans follows specific performance patterns, depending on what language the children speak.

> The pattern of development is like a game of leapfrog, with some aspects of our numerical competence emerging before our linguistic competence, and some aspects emerging afterwards. At present, we do not understand how these two domains of knowledge affect each other, either during the course of evolution or during development. (Hauser, 2000, p. 62)

A fundamental question in cognitive science is how language can shape number computation (Gelman & Butterworth, 2005; Hauser, Chomsky & Fitch, 2002). On the relationship between language and number, several studies with adults and neuroimaging have made significant progress in understanding how these systems interact (Houdé & Tzourio-Mazoyer, 2003). For example, in Russian-English bilinguals, practicing addition problems in Russian in which approximate answers are sought has no influence on performance of the same kind of math problems when performed next in English. In contrast, when addition problems performed in Russian require exact answers, performance is influenced when the same problems are carried out in English. This shows the effects of language on number computation, distinguishing the effects of language representation from the approximate large number system (Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999; Spelke & Tsivkin, 2001).

Some very interesting information on this issue should also be obtained through behavioral studies in developmental psychology that dissociate the numerical competence of brains with and without language, i.e. in children after age 2 and preverbal infants or non-human primates. Studies on infants have demonstrated that they can do simple arithmetic operations like 1 + 1 = 2 (Wynn, 1992), an ability that also exists in monkeys (Hauser, MacNeilage & Ware, 1996; Hauser, 2000). These experiments using a violation-of-expectation paradigm established that 5-month-olds can detect visually the error in 1 + 1 = 1 *and* 1 + 1 = 3 (this is considered a testimony to their ability to exactly calculate 1 + 1 = 2). Despite a debate on the nature of the underlying processes (Bryant, 1992; Simon, 1997, 1998; Wakeley, Rivera & Langer, 2000), the findings on addition in infants are robust and consistent (Wynn, 1998, 2000). Our experiments were based on the same paradigm except that we measured children's verbal reactions. Here we show that the number words that French-speaking toddlers learn make it hard for them to work out the results of some specific simple additions (including 1 + 1). These same additions cause no problems to toddlers who speak English. These results provide clear evidence of how the acquisition of a specific language influences directly number computation.

In a previous study (Houdé, 1997), we showed that French-speaking 2-year-olds responded correctly to 1 + 1 = 1 ('It's not okay') but failed on 1 + 1 = 3, where they thought it was okay 'because there are lots'. Only 3-year-olds were able to achieve verbal performance as accurate as the visual performance of 5-month-olds and monkeys. Our interpretation of this marked developmental lag was that it stems from interference between early arithmetic abilities and the later acquisition of number within language, i.e. the singular (1) opposed to the

Address for correspondence: Olivier Houdé, UMR 6194, CNRS, CEA, Université Paris-5, Sorbonne, 46 rue Saint-Jacques, 75005 Paris, France; e-mail: olivier.houde@paris5.sorbonne.fr

plural, which encompasses all other numbers treated as a whole (the set '2, 3, 4, . . .'). In French, unlike English for example, the same word (*un*) is used to represent singularity both as a cardinal value in the ordinal sequence of number words *un*, *deux*, *trois*, . . . (one, two, three, . . .) *and* as an indefinite article in the singular–plural opposition *un–des* (a–some). The operation 1 + 1 = 3 may therefore be erroneously accepted by 2-year-olds simply because the outcome (= 3) is plural and as such, differs from the starting point (1) which is singular. That is, we suspected that our French children's difficulty on event 1 + 1 = 3 lay in partially conflating the singular–plural distinction with the cardinal value system. Hence, our prediction was that the interference between early arithmetic abilities and number-in-language acquisition should be smaller, if it occurs at all, in English-speaking children than in their French counterparts. In addition, we predicted that if the singular–plural opposition is not part of the experimental design (i.e. a violation whose starting point is plural, 2 + 1 = 4 for example, rather than singular), the above interference should disappear.

Experimental design and results

Participants

Eighty French-speaking and 80 English-speaking children at the age of 2 or 3 participated in Experiment 1. The French-speaking children (half girls and half boys) were divided into two age groups, one composed of 40 2-year-olds (mean age 2 years, 7 months; range 2;2 to 3;0) and the other composed of 40 3-year-olds (mean age 3 years, 7 months; range 3;2 to 4;0). They were from three childcare centers and one nursery school located in Paris, France. The English-speaking children (half girls and half boys) were also divided into two age groups, one of 40 2-year-olds (mean age 2 years, 6 months; range 2;0 to 2;11) and the other of 40 3-year-olds (mean age 3 years, 6 months; range 3;0 to 3;11). They were from six nursery schools located in Oxford, England. The French- and English-speaking children were all from middle-class homes, and the social and economic backgrounds of the two populations were equivalent.

Stimuli and procedure

Within each age group, half of the subjects were randomly assigned to one of two conditions, depending on which type of arithmetic event was presented in the violation-of-expectation paradigm (adapted from Wynn's studies; Wynn, 1992). In the first condition, the starting point of the mental arithmetic operation was singular, i.e. events 1 + 2 = 2, 1 + 2 = 3 and 1 + 2 = 4. The children were shown both unexpected events twice (1 + 2 = 2 and 1 + 2 = 4), each associated with the expected event (1 + 2 = 3). This made four event pairs that differed by their violating outcome, hereafter denoted = 2 and = 4. In the second condition, the procedure was the same except that the starting point of the operation was plural, i.e. events 2 + 1 = 2, 2 + 1 = 3 and 2 + 1 = 4.

Items were manipulated in a play theatre. First we showed each child either 1 or 2 Mickey Mouse dolls on a platform; then we placed a screen in front of the platform so that the child could no longer see the dolls. After that we added either 1 or 2 more dolls to those on the platform. The child could clearly see how many dolls we added but, because of the screen, could not see how many dolls were now there. Then on some trials we surreptitiously changed the number of dolls on the platform, thus producing erroneous results; on other trials we did not tamper with the addition. Finally we lifted the screen and asked the child to accept the number of dolls as right or to reject it. For the French-speaking children, the very popular elephant, Babar, was used instead of Mickey Mouse (materials taken from our previous study; Houdé, 1997). Trials alternated between outcomes = 2, = 3, and = 4 and were counterbalanced as follows: 2-3-4-3-2-3-4-3, 3-2-3-4-3-2-3-4, 4-3-2-3-4-3-2-3, 3-4-3-2-3-4-3-2. Each subject was assigned to one of these four patterns in both conditions. After familiarization with the character, the experimenter said to the child, 'Do you see this theater? Some Mickey Mouses (or Babars) will come into the theatre to play with you. You must carefully watch what they are doing and then tell me if it's okay or not and why, right?' The expressions 'okay' and 'not okay' were used to facilitate the child's response, in accordance with our previous study.[1] The children could obtain at most two points for each type of outcome violation (= 2 or = 4). One point was given for each event pair on which the child gave correct and justified verbal responses to *both* the unexpected event ('It's not okay') and the expected event ('It's okay').

Results

An ANOVA yielded a significant overall interaction between language (English or French), age (2 or 3), starting

[1] Unlike infant experiments based on looking time, the children's reactions measured were verbal. In order to avoid any potential comprehension bias linked to the use of words like 'impossible', 'magical' or 'strange', etc. to express rule violations, the instructions were made to be as simple as possible. The children were merely asked to say, 'okay' or 'not okay'. These instructions (tested during a preliminary survey) were designed to make it easy for these very young children to express their reactions to the impossible event, when perceived as such.

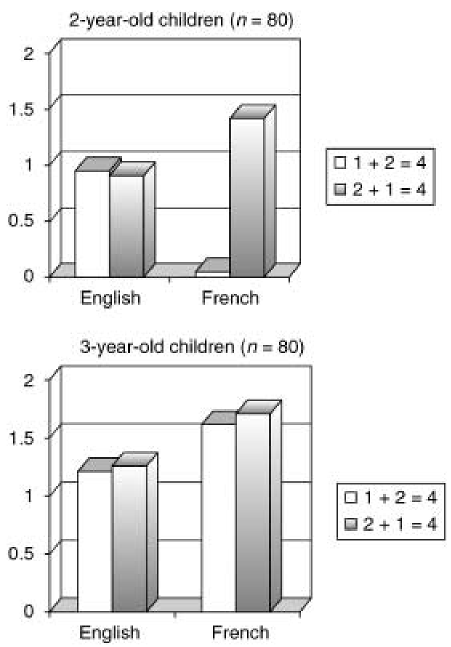

Figure 1 *Mean scores of English-speaking and French-speaking children for events 1 + 2 = 4 or 2 + 1 = 4 (i.e. ability to detect unexpected events = 4).*

condition (singular or plural: 1 + 2 or 2 + 1), and outcome violation (= 2 or = 4) [$F(1, 152) = 5.08$, $p < .05$]. For the 2-year-olds, there was a significant interaction between the language and starting condition variables on the = 4 outcome violation [$F(1, 76) = 26.13$, $p < .0001$] (see Fig. 1). The English-speaking children had many more correct verbal responses (detections of the violation) to event 1 + 2 = 4 than their French counterparts [$F(1, 38) = 31.09$, $p < .0001$]. This result confirmed our main prediction, that the singular/plural opposition, specifically triggered here by the event 1 + 2 = 4 (in which a singular starting point (1) was opposed to a plural violating outcome (4)) is a major difficulty for French-speaking 2-year-olds. By contrast, the French children at this age performed better on event 2 + 1 = 4 than the English children did [$F(1, 38) = 5.11$, $p < .05$]. Our additional prediction was also confirmed, then, since French-speaking 2-year-olds had no trouble with event 2 + 1 = 4, where the mental operation starts from a plural. The other events (1 + 2 = 2 and 2 + 1 = 2) were solved equally well by the two groups. Note that for events 1 + 2 = 2 and 2 + 1 = 2, no precise calculations were needed since 2 was already present in the operation. The unexpected outcome 2 was easy to detect as erroneous since the children only had to be able to expect an arithmetic operation to result in any kind of numerical change (thereby ruling out 1 and 2). For the 3-year-olds, the French-speaking children were still better performers on event 2 + 1 = 4 than the English ones [$F(1, 38) = 4.83$, $p < .05$], but they were no longer worse on event 1 + 2 = 4. The other events were solved equally well by the two language groups. The fact that for some arithmetic events, the French-speaking 2- or 3-year-olds were better than (or equal to) the English-speaking ones makes the main result (specific difficulty with 1 + 2 = 4 at age 2) even stronger.

Control experiment

To generalize these results, English-speaking children were tested, in an attempt to replicate our previous study conducted on French-speaking children with events 1 + 1 = 1, 2, or 3 (Houdé, 1997), i.e. exactly the same operations as in studies on preverbal infants (Wynn, 1992, 2000) and monkeys (Hauser *et al.*, 1996; Hauser, 2000). This was done in a second experiment, which used the same general procedure as in Experiment 1. The trials were counterbalanced as follows: 1-2-3-2-1-2-3-2, 2-1-2-3-2-1-2-3, 3-2-1-2-3-2-1-2, 2-3-2-1-2-3-2-1. Thirty-two English-speaking children at the age of 2 or 3 participated in Experiment 2 (half girls and half boys). They were divided into two age groups, one composed of 16 2-year-olds (mean age 2 years, 7 months; range 2;1 to 2;11) and the other composed of 16 3-year-olds (mean age 3 years, 5 months; range 3;0 to 3;10). They were from three nursery schools located in Oxford.

The results showed that, already at the age of 2, there was no significant performance difference between events 1 + 1 = 1 and 1 + 1 = 3 (see Fig. 2). Performance was very good at both ages and for both event types. These findings are strongly contrasted with our earlier results on French-speaking 2-year-olds (included in Fig. 2), for whom event 1 + 1 = 3 was particularly difficult. Thus, as in Experiment 1, when a singular starting point was opposed to a plural outcome (here, 1 vs. 3), English-speaking 2-year-olds were dramatically better than their French counterparts at detecting the arithmetic violation.

Discussion

Our results concern a precise developmental window (2- and 3-year-old children) and demonstrate that, although a general arithmetic ability shared by preverbal infants and monkeys most certainly exists, the ontogeny of such initial knowledge in the human brain follows different performance patterns, depending on what specific language the young children speak. Findings in Russian-English bilingual college students suggest that the particular natural language a person speaks plays a role in representations of large numbers, but not in the representations of

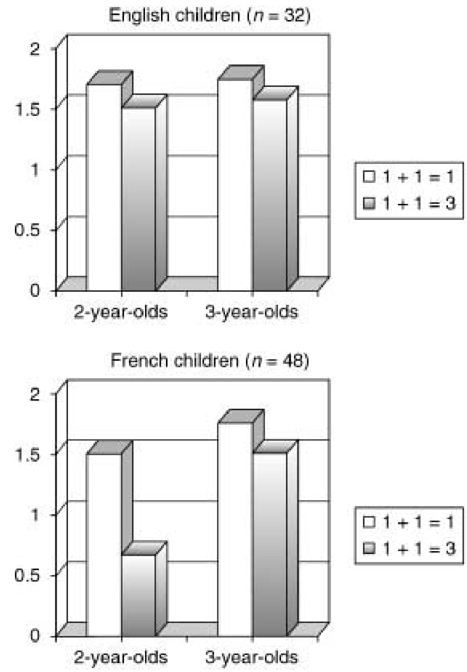

Figure 2 *Mean scores of English-speaking and French-speaking children for events 1 + 1 = 1 or 3 (i.e. ability to detect unexpected events = 1 and = 3). Data concerning French-speaking children (mean age 2 years, 8 months; range 2;1 to 3;0, for the 2-year-olds, and mean age 3 years, 10 months; range 3;3 to 4;0, for the 3-year-olds) are taken from our previous study (Houdé, 1997). The ANOVA yielded a significant difference at* $p < .05$ [$F(1, 22) = 5$] *between the 2-year-olds' performance on events 1 + 1 = 1 and 1 + 1 = 3. The French- and English-speaking children were all from middle-class homes, and the social and economic backgrounds of the two populations were equivalent.*

small numbers which humans share with other mammals (Dehaene *et al*., 1999; Spelke & Tsivkin, 2001). Here, we show in young children that an interaction between natural language and arithmetic also exists for small-number representations at an earlier stage of human development.

Thus, by taking into account a specific difference between French and English, we have provided a cross-linguistic demonstration of the human shift from visual-spatial arithmetic (in monkeys and preverbal infants) to symbolic-linguistic arithmetic (in toddlers). However, the limitation of this kind of cross-linguistic study is that factors other than language (e.g. education) could have differed between our French and English samples. Nevertheless, our developmental data provide new fuel for the current debate about the relationship between language and number (Gelman & Butterworth, 2005; Houdé & Tzourio-Mazoyer, 2003; see also the recent findings from Amazonian cultures that have very restricted number vocabularies: Gordon, 2004; Pica, Lemer, Izard & Dehaene, 2004).

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