[Mind, Brain and Education]

Nonverbal ability and scientific vocabulary predict children's causal reasoning in science better than generic language

Running title: Nonverbal ability in causal reasoning

Selma Dündar-Coecke and Andrew Tolmie

Centre for Educational Neuroscience and Department of Psychology and Human Development, UCL Institute of Education, University College London

Acknowledgement: This research was funded by a grant from the Institute of Education, University College London, and an award from the UK Economic and Social Research Council to the first author.

Abstract

Verbal and nonverbal forms of thinking exhibit widespread dissociation at neural and behavioral level. The importance of this for children's causal thinking and its implications for school science are largely unknown. Assessing 231 5-10-year-olds' responses: verbal ability predicted causal reasoning, but only at lower levels, while nonverbal ability was the strongest predictor at higher levels of causal inference. We also distinguished generic/scientific vocabulary use for 101 children to see if this furthered understanding. Use of scientific vocabulary predicted causal reasoning beyond generic, and connected more to nonverbal thinking. Parental education showed a marginally significant interaction with nonverbal ability, and was associated with its differential effects. The findings highlighted (1) the importance of elementary school science activities supporting application of nonverbal ability in thinking about causal processes, (2) the benefits of linking nonverbal imagery directly to scientific vocabulary, (3) shortcomings in understanding of the forms/sources of nonverbal ability and their role in learning.

Keywords: causal cognition; nonverbal ability; science; scientific vocabulary; socioeconomic status; verbal ability

One aspect of scientific thinking is acquiring knowledge about the causal mechanisms whereby operative factors produce consistent effects. Knowledge of this kind can be verbal – explicit coding of causal relations in language (cf. Nelson, 1996, and Tomasello, 1999 on the use of syntactic structures to capture the direction and nature of phenomena). It can also be nonverbal, where representations of cause-effect relationships take the form of sensory impressions observed from spatial-temporal characteristics of dynamic events (Bullock, 1984, 1985; Dündar-Coecke, Tolmie, & Schlottmann, submitted), or generated by patterns detected from statistical analyses (Cheng & Holyoak, 1985; Schulz et al., 2008). This raises the possibility that causal knowledge requires connections to be made between various implicit forms and expressive language. It is, however, unknown whether this also means that verbal and nonverbal capacities have essentially independent influences on causal thinking, which would have important implications for science instruction. The aim here is to understand this through children's reasoning about causal processes, while language abilities are undergoing broad development.

Verbal and nonverbal thinking in science

Explicit concepts are separate from perceptual representations (Mandler, 2004). This separation in the context of science learning is supported by diSessa (e.g. 2006, 2018), who theorises that children's explicit knowledge regarding causal phenomena is constructed bottom up out of sensory and perceptual elements. However, evidence indicates that implicit and explicit aspects of children's causal knowledge have distinct developmental trajectories. Nonverbal representations rapidly increase in accuracy through the elementary school years (see e.g. diSessa, 1988; Howe et al., 1999, Symons et al., 2015), while verbal representations develop more slowly, and are often less accurate (e.g. Hast & Howe, 2015; Wilkening & Cacchione, 2011). These differences have important implications for science education, since they indicate that current emphases on teaching via verbal instruction fail to facilitate integrated understanding. We argue that this lack of integration may arise because of a previously unrecognised functional separation between the verbal and nonverbal neural systems that operate when children observe and think about causal phenomena.

The forms nonverbal thinking can take have not been explored by behavioural research to the same extent as verbal ones (see e.g. Bishop et al., 2016, for areas investigated in the linguistic domain), though traditional nonverbal measures test visual and fluid reasoning (DeThome & Schaefer, 2004; Raven, 2000; see Caroll, 1993 for evidence from factor analyses). This lack of interest has been paralleled by failure to consider the potential importance of the nonverbal domain in science learning. The only available evidence is recent, indicating apparent quality of explanation might reflect limited language but not limited reasoning (see Dündar-Coecke, Tolmie, & Schlottmann, 2019).

Neuroscience studies have been more searching, although they focus predominantly on adults. Research on the cerebral localization of visual and linguistic areas confirms the possibility that verbal and nonverbal systems are neuroanatomically segmented processes (Farah, 1989; Thierry & Price, 2008). In many studies, language processing was strongly lateralized to the left hemisphere and involved frontal, temporal, and parietal lobes (Binder et al., 1997; Damasio, 1996). In contrast, tests with split-brain patients showed that the isolated right hemisphere exhibited better performance on visuospatial tasks such as mental rotation (Corballis, Funnell, & Gazzaniga, 2002; Funnel et al., 2003). Other studies showed activation associated with nonverbal tasks involved the prefrontal cortex and other areas related to sensory encoding in the posterior cortex, such as occipital, temporal, and parietal lobes (Cohen et al., 1996; Gray et al., 2003; O’Boyle et al., 2005; Vyshedskiy et al., 2017). This suggests that nonverbal tasks recruit broader cortical areas with distinct systems, and that tasks drawing on both verbal and nonverbal elements may stimulate different brain regions simultaneously.

Connecting nonverbal information to verbal may not be straightforward. This is not a unitary process, as language does not operate as an isolated module, and links to nonverbal processes in multiple ways. Considering how spatial cognition is captured in language, neural networks underlying nonverbal-analytical performance seem to overlap with verbal working memory networks, with parietal activation limited to the left hemisphere (Prabhakaran et al., 1997). The parieto-frontal integration theory of intelligence (P-FIT) accounts for brain regions associated with intelligence tasks, and suggests that isolation of the language network in nonverbal or spatial tasks is unlikely (Jung & Haier, 2007). However, spatial tasks primarily concern configurations of static properties. Everyday language appears to capture these more readily than the dynamic properties of processes involved in causal phenomena, because stable features of objects are easier to code (Mandler, 2004). Dynamic properties require greater abstraction, since the features of these are transient (Chatterjee, 2008). Lateral temporal cortices deal with motion, action representations and action verbs – intrinsic time-based changes; while dorsal regions deal with extrinsic properties, such as paths of motions, locative representations, and prepositions (see also Papafragou, Massey, & Gleitman, 2002, for a review). This compounds the complexity of making connections: dynamic features are not just harder to code, but multiple systems are involved in doing so. It is therefore likely to be an effortful, not a purely perceptual process.

Behavioural studies confirm the implications of the neural evidence (see Hermer-Vazquez, Spelke, & Katsnelson, 1999, on the role of natural language in spatial memory when using geometric and non-geometric information to relocate the body; though see also Ratliff & Newcombe, 2008). Recent evidence indicates that measures of children’s spatial cognition consistently share variance with verbal ability, suggesting children make widespread use of verbal coding strategies for spatial thinking. In contrast, measures of children’s dynamic spatial-temporal cognition had unique variance beyond verbal ability, and were linked more with nonverbal in predicting causal mechanisms (Dündar-Coecke et al., submitted). Not only does making connections involve multiple systems then, but as the focus of causal reasoning shifts from basic causal factors (static features of objects as captured by spatial tasks) to thinking about dynamic causal mechanisms (dynamic features as captured by spatial-temporal tasks), verbal and nonverbal representations seem to become more distinct.

The effects of verbal-nonverbal dissociation in science learning

In school science, therefore, capturing dynamic properties of causal events in language may in particular be challenging for elementary age children. This is likely to be especially true when causal processes that extend over time are considered; e.g. when an object sinks, burns, or dissolves, continuous *processes* need to be conceived as chains of causal events. As compared to events, causal processes need contrasting demonstrations and specific modes of information presentation beyond verbal explanations to facilitate children’s capacity to make inferences from these, increasing perceptual demands further (Dündar-Coecke & Tolmie, submitted a). The ability to capture these becomes highly crucial in later learning, where scientific laws need to be grasped that involve more complex deterministic or continuous random processes. If perceptual representations are constructed first (cf. diSessa, 2018) and coding in language is difficult, nonverbal ability may be the more important driver of performance for causal cognition as it progresses from the visible and concrete to the invisible, abstract and dynamic characteristics of phenomena. Science teaching may therefore need to do more to support the growth of nonverbal representations.

At present this is unknown, however. We aimed to test whether (1) verbal and nonverbal ability have independent effects on children's causal reasoning about continuous natural processes, as outlined above; and if so (2) whether this leads to differential influences on children's reasoning, with nonverbal ability becoming more important as performance progresses. We also considered the possibility that access to more specialised 'scientific vocabulary' may assist connections between nonverbal representations and language. Most field-specific/scientific terms are reserved for encoding specific features of causal phenomena, including the dynamic aspects of these, in contrast to multipurpose everyday vocabulary (e.g. at elementary level, 'force' versus 'push'). Such vocabulary seems to correspond to more abstract level semantic information regarding transient dynamic processes, and may provide crucial verbal indices that facilitate coding of perceptual impressions in language. It may therefore be more related to nonverbal representations than generic vocabulary. This parallels the dual pathways involved in processing concrete and abstract words (Kiehl et al., 1999; Paivio, 1971; Walker & Hulme, 1999), but adds an additional layer since the concrete/abstract distinction is insufficient to deal with the specific nature of causal cognition.

Finally, we also considered whether the difficulties of coding into generic and scientific language might be greater for those from less advantaged contexts, since children's socioeconomic background affects their verbal and nonverbal performance, as well as interest in science (Nunes et al., 2017). The present research therefore explored both the general relationship of verbal and nonverbal ability to different levels of causal reasoning, and how far this interacts with children’s home environment.

METHODS

Participants

A broad sample of 231 children spanning the English primary school range was recruited from five schools in London and Oxford (71 from Year 1 [Y1], mean age = 6 years, 0 months, sd = 4.3 months; 78 from Year 3 [Y3], mean age = 8 years, 1 month, sd = 5.3 months; 82 from Year 5 [Y5], mean age = 10 years, 0 months, sd = 6.1 months). All children participated with parental consent; the research was approved by the UCL Institute of Education Research Ethics Committee.

Of 227 parents who responded to a questionnaire addressing occupation and educational level, 20 (8.8%) were unemployed, 40 (17.6%) were manual workers, 65 (28.6%) were self-employed/non-manual workers, and 102 (44.9%) were professionals, indicating that although children from all sections of the workforce were represented, there was oversampling at the top of the range (overall percentages in these categories for England are 6.2%, 35.0%, 47.4% and 11.4% respectively; Office for National Statistics, 2014); accordingly, 36 (15.9%) had only GCSE (basic secondary school) qualifications; 27 (11.9%) had A levels (higher secondary); 77 (33.9%) had undergraduate degrees; 55 (24.2%) had a postgraduate degree/professional qualification; and 32 (14.1%) had doctoral degrees. In total, 45.4% heard languages in addition to English in the home, indicating substantial ethnic and linguistic diversity (England in total = 20.6%; Department for Education, 2017).

Materials and Procedure

Children were tested on five tasks in one-to-one sessions out of class lasting approximately 30 minutes each. Task order was as below. Responses were recorded manually, but the causal tasks were also audio-recorded for later checking.

The *expressive vocabulary* and *block design* subtests from the Wechsler Abbreviated Scale of Intelligence (WASI-II) (Wechsler, 2011) were used to provide measures of verbal and nonverbal ability. Administration and scoring followed standard procedures. The sample spanned the normal range, but with above average means, especially for verbal ability (see Table 1 for mean raw scores; Wechsler, 2011, for norms). The mean age equivalent for verbal and nonverbal ability for Y1 was 8 years, 9 months and 7,2 respectively; for Y3, 11,9 and 8,8; and for Y5, 14,11 and 11,2.

Causal reasoning was assessed by three mini-experiments relevant to physics, biology and chemistry that addressed in turn sinking, absorption and solution, as described in Dündar-Coecke et al. (2019). Each involved a contrast between two exemplars that differed in the speed at which the target process occurred (see Dündar-Coecke & Tolmie, submitted a, for evidence on the advantages of contrasting simultaneous presentations for causal inference). Children inspected the materials and 1) predicted what would happen when they were placed into water; 2) watched carefully and described what they actually saw; 3) explained why they thought things had happened the way they had seen. They were encouraged to give full answers at each point.

Predictions and descriptions were scored 0-2 for accuracy of anticipating/reporting different sinking/absorption/solution rates for the two exemplars. Explanations were given incremental scores 0-3 for identifying relevant factors (e.g. weight for sinking, thickness/hardness for absorption, grain size for solution); identifying differences between exemplars with respect to these; and describing the causal mechanism involved (weight relative to upthrust in sinking; facilitation of water rising by material structure in absorption; grain size/surface area affecting interaction with water in solution). Responses were scored independently by two researchers, with agreement ranging from 80% to 100% across the nine combinations of score and task, and an overall rate of 93%. Final scores were assigned following discussion/checking audio records if they differed. A composite score for causal reasoning (max=21) was generated by combining prediction, description and explanation components across the three mini-experiments (alpha = .702).

The causal task responses of a subsample of children (n=101, selected randomly in equal numbers from those who had low, middle and high causal reasoning scores) were inspected further for use of *scientific vocabulary*. This subsample did not differ significantly from the remaining children on age, parental occupation/education, vocabulary or block design; their causal reasoning scores were marginally higher, mean=12.93 versus 11.80, t(229)=2.130, p=.035. Scientific vocabulary was defined as terms that went beyond the everyday discourse typically used by children, i.e. specialised terminology capturing aspects of the three phenomena in more precise fashion. The Appendix lists the terms that were included. The two researchers who scored the main causal measures listened independently to the recordings of the selected children, noting the different candidate terms employed within each of the mini-experiments; agreement rate on these was 85%. These lists were then discussed, and a final set agreed. The number of unique instances of each was totalled for each child to give an overall score.

RESULTS

One-way ANOVAs by age group on the performance measures showed significant increases with age and differences between Year 1, Year 3 and Year 5 on WASI vocabulary, block design, causal reasoning and scientific vocabulary (**Table 1**). There were no differences between age groups on the demographic measures, parental occupation and parental education.

The relationship of block design to causal reasoning was logarithmic (Rsquare=.308, linear=.261), indicating that it was marginally more discriminating at lower levels of performance; a logarithmically transformed score was employed for subsequent analyses to capture explained variance for this measure more accurately. Relationships to causal reasoning were linear for WASI vocabulary, scientific vocabulary, parental occupation and parental education. Partial correlations controlling for age showed causal reasoning was significantly related to all these five predictors, though most strongly to log block design (**Table 2**). WASI vocabulary, log block design and scientific vocabulary were all related to each other, with 12-15% shared variance. Parental education and occupation were strongly correlated with each other, but less so with the other predictors. Nevertheless, there were significant differences between levels of parental education – the stronger predictor of causal reasoning – on log block design, F(4,226)=5.472, p<.001, partial eta-squared=.090, and scientific vocabulary, F(4,96)=3.437, p=.011, partial eta-squared=.125. In both cases, these differences were due to children whose parents had the highest level of education performing significantly better than those at lower levels. There was no effect of parental education on WASI vocabulary, although there was a similar trend.

Effects of verbal and nonverbal ability on causal reasoning. Hierarchical regression (**Table 3**) was used to test for independent effects, with age in months entered at the first stage as a control variable, and WASI vocabulary and log block design at the second and third, in order to examine the impact of the weaker predictor first. The interaction between them was entered last. The beta for vocabulary dropped considerably with the inclusion of log block design, indicating a partial overlap in explained variance, but both were substantial and independent predictors, with nonverbal ability the stronger. There was no interaction.

Differential effects of verbal and nonverbal ability were tested using maximum likelihood path analysis to examine their relative strength, first within the lower and upper halves of the median split on causal reasoning scores, and then, to refine the picture at higher levels, within the upper quartile. The results are shown in **Figure 1**. In line with hypothesis, the influence of verbal ability waned relative to nonverbal ability as causal reasoning improved, while the influence of nonverbal ability increased, especially at the highest level of performance.

Relationships between scientific and generic vocabulary, nonverbal ability and their impact on causal reasoning. Principal components analysis with varimax rotation on the scores for scientific vocabulary, WASI generic vocabulary, and log block design (KMO=.706, sphericity p<.001) showed that each loaded on a separate factor, with no significant cross-loadings, scientific vocabulary = .933, log block design = .907, WASI vocabulary = .894.

Hierarchical regression (**Table 4**) was used to examine how far scientific vocabulary was also a distinct predictor of causal reasoning, entering it therefore ahead of WASI vocabulary and log block design. It was significant initially, and remained so when WASI vocabulary was entered, though its beta dropped substantially. When log block design was entered, both scientific and WASI vocabulary became non-significant (WASI remained marginal, p=.076). When log block design was entered before WASI vocabulary, scientific vocabulary became non-significant straight away. This confirmed nonverbal ability was the strongest predictor overall, but indicated that scientific vocabulary overlapped to a greater extent with this than general verbal ability in terms of explained variance in causal reasoning.

Using the median split on causal reasoning scores to examine the impact of scientific vocabulary at different levels, for the lower half, r=.176, p>.05, df=39; for the upper half, r=.353, p=.006, df=57. This difference in correlations was not significant, however, z=0.91, p=.181, despite the presence of a reliable association in the upper half only.

Effects of verbal and nonverbal ability on causal reasoning as a function of social background. Hierarchical regression was used to test the effects of parental education, entering it and interactions with WASI vocabulary/log block design after the main predictors, in order to examine whether it altered the outcomes noted above (**Table 5**). Including parental education led to modest reductions in the betas for vocabulary and more particularly log block design, but both remained significant predictors, alongside parental education itself. The interaction with log block design was marginal, p=.055, and positive, indicating combined benefits of better parental education and nonverbal ability at higher levels of causal reasoning. Parental education was not a significant predictor when this analysis was repeated with scientific vocabulary included, indicating weaker effects in that subsample.

Further partial correlations controlling for age were computed for causal reasoning with log block design and WASI vocabulary at each level of parental education. Results are presented in **Figure 2**, with the mean causal reasoning score (shown as proportion of maximum to make the scale comparable) included as an index for comparison. Causal reasoning increased across levels of parental education, in line with the regression analysis, and as it did so, there was a crossover effect in the relative impact of verbal and nonverbal ability, with the correlation between causal reasoning and nonverbal ability across the highest two levels of parental education significantly stronger than that between causal reasoning and verbal ability (z=1.805, p=.036, one-tailed).

Nonverbal ability was plainly the stronger driver of higher levels of causal reasoning, though perhaps to a different extent across children from more advantaged backgrounds. Those whose parents had doctoral degrees (level 5) showed a steeper increase for causal reasoning than children at other levels, and though nonverbal ability was still the stronger predictor, its power no longer paralleled the growth of causal reasoning. This suggests another factor may also be involved at this level. Although verbal ability provided support for causal reasoning among children at the lowest two levels of performance and social background, its effects tailed off at high levels.

DISCUSSION

Verbal and nonverbal thinking in science

The present study provided the first behavioural evidence on the primary questions we addressed: (1) both verbal and nonverbal ability were unique and major contributors to children's causal reasoning; (2) verbal ability was a stronger predictor of lower levels of causal reasoning, and nonverbal of higher. This is consistent with brain data, and supports the case for distinct neural systems being involved in causal reasoning – paralleling Cohen et al. (1996), Corballis et al., (2002), Gray et al. (2003) – with nonverbal systems primary. However, these neuroimaging studies employed static spatial tasks, and we have no evidence whether the networks involved in dynamic e.g. spatial-temporal representations are also distinctly detectable using imaging approaches. A further study is needed for comparison.

As in the brain data, the effects of verbal and nonverbal ability were not completely independent, even though they were clearly dissociable. However, their overlap in the prediction of causal reasoning may reflect their more equivalent joint influence at lower levels (see Figures 1 and 2, showing that at more sophisticated levels nonverbal ability is an important driver in causal thinking). This is consistent with connection between nonverbal and verbal processing being easier when children's focus was on the static/spatial features of the objects involved in the causal processes.

The effects of verbal-nonverbal dissociation in science learning

As children shifted to thinking about dynamic underlying mechanisms, the dissociation became more marked, and the impact of generic verbal ability reduced while that of nonverbal ability increased. This supports the argument that there is a trade-off in the use of verbal and nonverbal abilities in dynamic causal processes when children have no ready language available to connect perceptions to words.

Access to scientific vocabulary assisted performance, and its impact was distinct from generic vocabulary. Moreover, at the higher levels of causal reasoning, scientific vocabulary carried reliable benefit, and it overlapped with nonverbal ability in explained variance. The correlation between scientific and generic vocabulary suggests that it may grow out of everyday language competence, but it appears to bridge more to nonverbal knowledge and thus be more relevant to imagery. The latter remained the dominant influence, though, consistent with the argument that scientific vocabulary aids coding into language; it had no predictive power on its own.

We acknowledge, however, that the measure of scientific vocabulary we used here was limited to what children happened to use i.e. it captured performance not competence, so any conclusions must be tentative. There is substantial need for a standardised index of comprehension of scientific vocabulary to underpin further research on its impact. This would aid not just work on the development of causal reasoning, but wider research on neural networks associated with different levels of language. Work on the concrete-abstract distinction has shown that behavioural differences are consistent at the neurological level, with dissociable activation patterns for abstract and concrete words. An fMRI study by Binder et al. (2005) found both concrete and abstract words activated a left lateralized network, but although areas overlapped, bilateral association areas were also involved for concrete word processing (see also Kiehl et al., 1999; Damasio, 1996). Additional investigation along these lines can further understanding of whether the behavioural effects described here are detectible at brain level. At present, no evidence is available on whether scientific vocabulary corresponds neurally to abstract-conceptual or to abstract-perceptual/procedural knowledge.

This study provided a more sensitive index (one-to-one testing rather than computer-based or distance testing) of whether children’s home environment had an influence on these findings. We found positive effects of parental education, one of the most important socioeconomic parameters. These effects interacted marginally with nonverbal but not verbal ability, and were associated with the differential impact of nonverbal ability at higher levels of causal reasoning. However, at the very highest levels of causal reasoning and parental education, the effects of nonverbal ability seemingly waned. This suggests that as children’s focus on the mechanisms underlying continuous causal processes grew, they drew on another competence not assessed in this study. This may be spatial-temporal processing – cognition of dynamic processes – which Dündar-Coecke et al. (submitted) found was highly predictive of mechanism level inference together with nonverbal ability.

Overall, two main conclusions can be drawn from this research:

1. In terms of theory, both neural and behavioural evidence suggest that causal reasoning is not mediated by generic verbal ability, but draws substantially on nonverbal ability. However, ‘nonverbal’ is a generic term, and its forms need to be explored at both neural and behavioural level.
2. For school science, activities need to place much greater emphasis on promoting nonverbal awareness of causal processes, connecting that directly to appropriate scientific vocabulary. A classroom exercise with 5 to 8-year-olds has trialled this approach: children engaged in an imaginative game relating to sinking, and were then introduced to relevant scientific terminology (Dündar-Coecke & Tolmie, submitted b). This program produced substantial improvements in children’s grasp of causal mechanisms, and capacity to express this, regardless of age, providing a potential template for future interventions and classroom implementations.

These findings are significant when next generation science standards are considered, where children are expected not just to learn content but to grasp the procedural and intellectual methods used in science, engineering, and other relevant fields.

REFERENCES

Binder, J.R., Frost, J.A., Hammeke, T.A., Cox, R.W., & et al. (1997). Human brain language areas identified by functional magnetic resonance imaging. *Journal of Neuroscience, 17(1)*, 353-362.

Binder, J.R., Westbury, C.F., Mckiernan, K.A., Possing, E.T., & Medler, D.A. (2005). Distinct brain systems for processing concrete and abstract concepts. *Journal of Cognitive Neuroscience, 17(6)*, 905-917.

Bishop D., Snowling M., Thompson P., & Greenhalgh T. (2016). CATALISE-2 consortium. CATALISE: a multinational and multidisciplinary Delphi consensus study of problems with language development. Phase 2. Terminology. *PeerJ Preprints*4, *e2484v1.*

Bullock, M. (1984). Preschool children's understanding of causal connections. *British Journal of Developmental Psychology, 2,* 139-148.

Bullock, M. (1985). Causal reasoning and developmental change over the preschool years. *Human Development, 28,* 169-191.

Carroll, J.B. (1993). *Human cognitive abilities: a survey of factor-analytic studies*. USA: Cambridge University Press.

Chatterjee, A. (2008). The neural organization of spatial thought and language. *Seminars in Speech and Language, 29*(3), 226–238.

Cheng, P. W., & Holyoak, K. J. (1985). Pragmatic reasoning schemas. *Cognitive Psychology, 17*, 391–416.

Cohen, M.S., Kosslyn, S.M., Breiter, H.C., DiGirolamo, G.J., Thompson, W.L., Anderson, A., Bookheimer, S., Rosen, B.R., & Belliveau, J. (1996). Changes in cortical activity during mental rotation: a mapping study using functional MRI. *Brain, 119*, 89–100.

Corballis, P.M., Funnell, M.G., & Gazzaniga, M.S. (2002). Hemispheric asymmetries for simple visual judgments in the split brain. *Neuropsychologia, 40,* 401–410.

Damasio, A.R. (1996) A neural basis for lexical retrieval. *Nature, 380,* 499–505.

Department for Education (2017). Schools, pupils and their characteristics, January 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/650547/SFR28_2017_Main_Text.pdf

DeThome, L.S., & Schaefer, B.A. (2004). A guide to child nonverbal IQ measures. *American Journal of Speech-Language Pathology, 13(4),* 275-290.

diSessa, A. (1988). Knowledge in pieces. In G. Forman & P. Pufall (Eds.), *Constructivism in the computer age* (pp. 49–70). London: Lawrence Erlbaum Associates, Publishers.

diSessa, A. (2006). A history of conceptual change research: Threads and fault lines. In R. K. Sawyer (Ed.), The Cambridge handbook of the learning sciences (pp. 265-281). Cambridge: Cambridge University Press.

diSessa A.A. (2018) A friendly introduction to “Knowledge in Pieces”: Modeling types of knowledge and their roles in learning. In G. Kaiser, H. Forgasz, M. Graven, A. Kuzniak, E. Simmt, & B. Xu (Eds.), *Invited lectures from the 13th International Congress on Mathematical Education. ICME-13 Monographs*. Springer Open.

Dündar-Coecke, S., & Tolmie, A. (submitted a). What makes causal mechanisms more accessible across development?

Dündar-Coecke, S., & Tolmie, A. (submitted b). A short-term intervention improved children's insights into causal processes.

Dündar-Coecke, S., Tolmie, A., & Schlottmann, A. (2019). Children's reasoning about causal processes: the role of verbal and nonverbal ability. *British Journal of Educational Psychology*.

Dündar-Coecke, S., Tolmie, A., & Schlottmann, A. (submitted). The role of spatial and spatial-temporal analysis in children's causal cognition of continuous processes.

Farah, M.J. (1989). The neural basis of mental imagery. *Trends in Neuroscience, 12(10),* 395-399.

Funnell, M.G., Corballis, P.M., & Gazzaniga, M.S. (2003). Temporal discrimination in the split brain. *Brain and Cognition, 53,* 218–222.

Gray, J. R., Chabris, C. F. & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience, 6(3),* 316–22.

Hast, M., & Howe, C. (2015). Children's predictions and recognition of fall: The role of object mass. *Cognitive Development,* 36, 103-110.

Hermer-Vazquez, L., Spelke, E., & Katsnelson, A. (1999). Sources of flexibility in human cognition: Dual task studies of space and language. *Cognitive Psychology, 39,* 3–36.

Howe, C.J., Tolmie, A., & Sofroniou, N. (1999). Experimental appraisal of personal beliefs in science: constraints on performance in the 9 to 14 age group. *British Journal of Educational Psychology*, 69, 243-274.

Jung, R.E., & Haier, R.J. (2007). The parieto-frontal integration theory (P-FIT) of intelligence: converging neuroimaging evidence. *Behavioral and Brain Science, 30,* 135–187.

Kiehl, K.A., Liddle, P., Smith, A.M., Mendrek, A., Forster, B.B., & Hare R.D. (1999). Neural pathways involved in the processing of concrete and abstract words. *Human Brain Mapping, 7,* 225–233.

Mandler J.M. (2004). *The foundations of mind: origins of conceptual thought*. New York: Oxford University Press.

Nelson, K. (1996). *Language in cognitive development: The emergence of the mediated mind*. Cambridge: Cambridge University Press.

Nunes, T., Bryant, P., Strand, S., Hillier, J., Barros, R., & Miller-Friedmann, J. (2017). Review of SES and science learning in formal educational settings. London: Education Endowment Foundation.

O'Boyle, M.W., Cunnington, R., Silk, T.J., Vaughan, D., Jackson, G., Syngeniotis, A., & Egan, G.F. (2005) Mathematically gifted male adolescents activate a unique brain network during mental rotation. *Brain Research: Cognitive Brain Research, 25(2),* 583–87.

Office for National Statistics (2014). National statistics socio-economic classification. https://www.nomisweb.co.uk/census/2011/ks611uk

Paivio A. 1971. *Imagery and verbal processes*. New York: Holt, Rinehart and Winston.

Papafragou A., Massey C., & Gleitman L. (2002). Shake, rattle, 'n' roll: the representation of motion in language and cognition. *Cognition, 84,* 189– 212.

Prabhakaran, V., Smith, J.A., Desmond, J.E., Glover, G.H., & Gabrieli, J.D. (1997). Neural substrates of fluid reasoning: An fMRI study of neocortical activation during performance of the Raven's Progressive Matrices test. *Cognitive Psychology, 33(1),* 43–63.

Ratliff, K.R., & Newcombe, N.S. (2008). Is language necessary for human spatial reorientation? Reconsidering evidence from dual task paradigms. *Cognitive Psychology, 56,* 142–163.

Raven, J. (2000). *Manual for Raven's progressive matrices and vocabulary scales Section 3: Standard progressive matrices: introducing the parallel and plus versions of the tests*. Oxford: Oxford Psychologists.

Schulz, L. E., Goodman, N. D., Tenenbaum, J. B., & Jenkins, A. C. (2008). Going beyond the evidence: Abstract laws and preschoolers' responses to anomalous data. *Cognition, 109(2),* 211-223.

Symons, G., Tolmie, A., & Oaksford, M. (2015). Source reliability in the development of children's understanding of causal systems. EuroAsianPacific Joint Conference on Cognitive Science, Turin.

Thierry, G., & Price, C.J. (2008). Dissociating verbal and nonverbal conceptual processing in the human brain. *Journal of Cognitive Neuroscience, 18(6),* 1-11.

Tomasello, M. (1999). *The cultural origins of human cognition*. Cambridge MA: Harvard University Press.

Vyshedskiy, A., Dunn, R., & Piryatinsky, I. (2017). Neurobiological mechanisms for nonverbal IQ tests: Implications for instruction of nonverbal children with autism. *Research Ideas and Outcomes 3,* e13239.

Walker I., & Hulme C. (1999). Concrete words are easier to recall than abstract: evidence for a semantic contribution to short-term serial recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25,* 1256–1271.

Wechsler, D. (2011). *Wechsler abbreviated scale of intelligence, second edition (WASI-II).* San Antonio, TX: NCS Pearson Education.

Wilkening, F., & Cacchione, T. (2011). Children's intuitive physics. In U. Goswami (Ed.), *The Wiley-Blackwell Handbook of Childhood Cognitive Development* (pp. 473-496). Oxford: Wiley-Blackwell.

Tables

Table 1

Means (standard deviations) for each age group on the test measures.

	Age group		
	Y1	Y3	Y5
WASI vocabulary	22.68 (5.31)	29.78 (5.46)	34.77 (4.91)
Block design	12.17 (5.82)	17.60 (8.27)	28.81 (12.24)
Causal reasoning	10.34 (3.89)	12.26 (3.63)	14.03 (2.91)
Scientific vocabulary	1.66 (1.15)	3.34 (1.89)	5.55 (3.82)
Parental occupation	3.23 (0.93)	3.01 (1.03)	3.06 (0.99)
Parental education	3.16 (1.10)	3.01 (1.03	3.06 (0.99)

WASI vocabulary: F(2,228)=102.295, Welch statistic=105.384 (df = 2, 149.716); *block design*: F(2,228)=64.369, Welch statistic=61.343 (2, 146.425); *causal reasoning*: F(2,228)=21.393, Welch statistic=22.069 (2, 145.425); *scientific vocabulary*: F(2,99)=19.158, Welch=23.305 (2, 59.644); p<.001 for all; differences between each age group are significant at p<.005 for all, except scientific vocabulary Y1 v Y3, p<.05; *parental occupation*: F(2,224)=0.947, Welch=0.984 (2, 148.230); *parental education*: F(2,224)=0.242, Welch=0.252 (2, 148.752); p>.05 for all.

Table 2

Partial correlations between measures, controlling for age (significant associations in bold).

	WASI vocabulary	Block design (logarithmic)	Scientific vocabulary	Parental education	Parental occupation
Causal reasoning	**.345*****	**.412*****	**.359*****	**.347*****	**.307*****
WASI vocabulary		**.356*****	**.392*****	**.147***	.107
Block design (logarithmic)			**.379*****	**.212****	**.135***
Scientific vocabulary^{+}				**.378*****	**.292****
Parental education					**.791*****

N=226 due to missing date of birth data for one participant and missing parental information for four; $^{+}$N=102, reflecting subsampling. *p<.05, **p<.01, ***p<.001

Table 3
Hierarchical regression analysis with causal reasoning score as dependent variable (significant predictors in bold).

Model	M1	M2	M3	M4
Predictor		β		
Age in months	**.435*****	.145	.025	.030
WASI vocabulary		**.424*****	**.279*****	**.274****
Block design (log)			**.370*****	**.365*****
Vocab x block design				-.057

AdjRsquare = .354; ΔR^2 = .190*** for M1; .096*** for M2; .077*** for M3; .003 for M4. $^{*}p$ <.05. $^{**}p$<.01. $^{***}p$<.001.

Table 4
Hierarchical regression analysis including scientific vocabulary, with causal reasoning score as dependent variable (significant predictors in bold).

Model	M1	M2	M3	M4
Predictor		β		
Age in months	**.569*****	**.401*****	.186	.128
Scientific vocabulary		**.339*****	**.214***	.125
WASI vocabulary			**.392****	.200
Block design (log)				**.419*****

AdjRsquare = .545; ΔR^2 = .324*** for M1; .087*** for M2; .066** for M3; .086*** for M4. $^{*}p$ <.05. $^{**}p$<.01. $^{***}p$<.001.

Table 5
Hierarchical regression analysis including parental education, with causal reasoning score as dependent variable (significant predictors in bold).

Model	M1	M2	M3	M4	M5
Predictor			β		
Age in months	**.432*****	.140	.019	.070	.073
WASI vocabulary		**.427*****	**.281*****	**.256****	**.249****
Block design (log)			**.371*****	**.318*****	**.304*****
Parental education				**.231*****	**.228*****
Parent ed x vocab					-.063
Parent ed x block					.122

AdjRsquare = .406; ΔR^2 = .187*** for M1; .097*** for M2; .078*** for M3; .051*** for M4; .010 for M5. $^{*}p$ <.05. $^{**}p$<.01. $^{***}p$<.001.

Fig. 1. Path models including standardised coefficients for the effects of WASI vocabulary and log block design on causal reasoning (subsidiary relationships in grey).

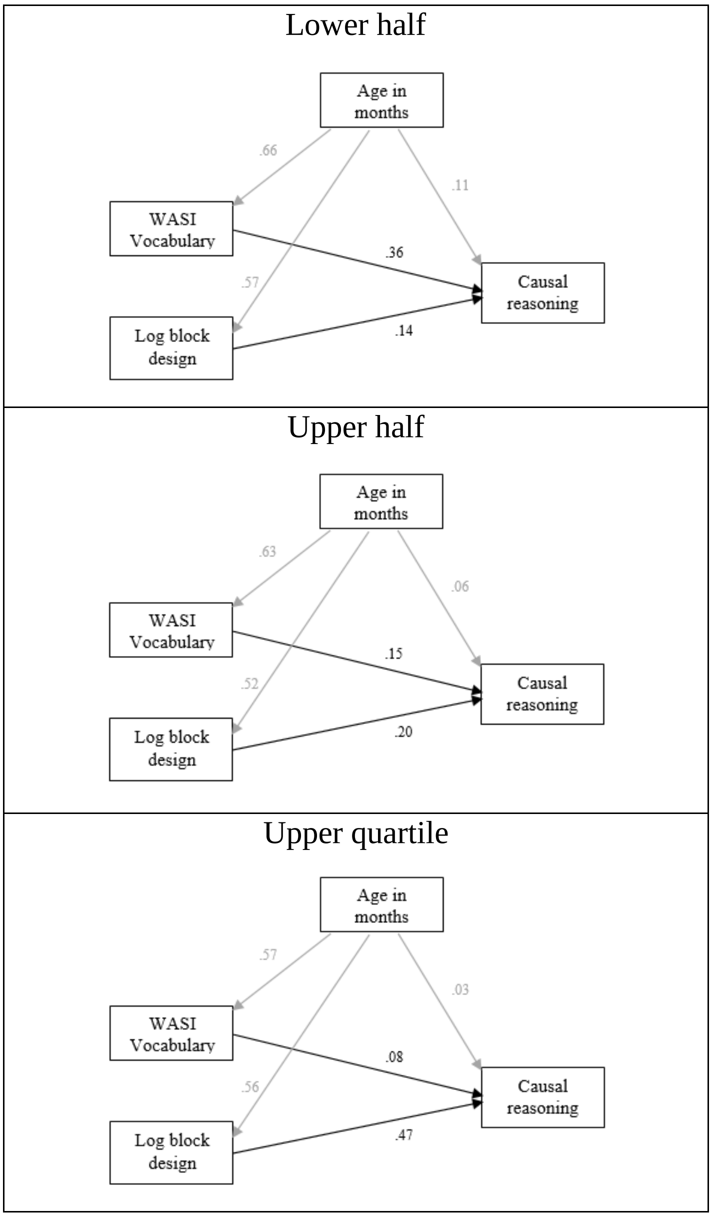
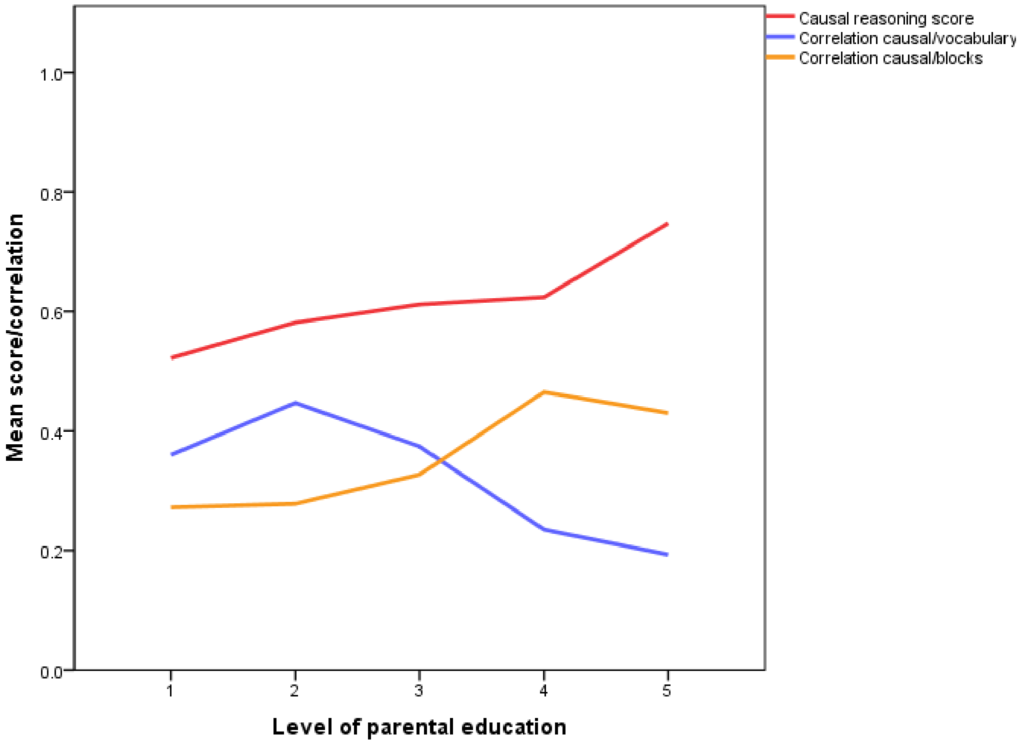


Fig. 2. Relationships between level of parental education, mean causal reasoning performance and correlation of causal reasoning to log block design and WASI vocabulary.



APPENDIX

Table A1
List of terms counted as scientific vocabulary (number of children using each in parentheses).

Sinking	Absorption	Solution
Air pocket (1)	Absorption/absorbency/absorbent (26)	Camouflaging (1)
Artificial (1)	Atoms (3)	Chemical (2)
Atomic level (1)	Bleached (1)	Compressed (1)
Balance (1)	Channelling (1)	Connect (1)
Buoyancy (1)	Durable (1)	Crystal/crystallised (2)
Carbon (1)	Expansion (1)	Disintegration (1)
Concrete (1)	Flexible (1)	Dissolving (37)
Depth (1)	Layer/tube/gap (9)	Dissolving time (1)
Drifted diagonally (1)	Line/straight line (11)	Evaporation (6)
Effect (1)	Magnetic (1)	Grain (3)
Float (55)	Manufactured (1)	Heaviness (1)
Force (1)	Moisture (1)	Invisible (3)
Gravity (10)	Pattern (2)	Melt (14)
Hydrogen (1)	Process (2)	Melting point (1)
Interior weight (1)	Recycle (1)	Mineral (1)
Liquid (2)	Resistance (1)	Molecule (2)
Mass (2)	Speed (5)	Reaction (2)
Natural (1)	Storage (1)	Shrinking (1)
Object (3)	Texture (3)	Solution (3)
Oxygen (2)	Waterproof (3)	Surface area (2)
Particle (1)		Translucid (1)
Pressure (2)		Transparent (2)
Sink/sinking (81)		Water-hating (1)
Sinking rate (1)		Water-loving (1)
Solid (10)		
Space (9)		
Still water (1)		
Substance (6)		
Surface (11)		
Time (10)		
Weight (17)		

Notes: 1) sinking was counted, since it is the correct technical term for the process of descending through liquid – many children failed to use this, talking instead about falling/going down/dropping; 2) line/gap/layer were included as more precise ways of describing the structure/texture of paper; 3) melt was allowed as a means of capturing the change in state during dissolving; 4) speed/time were allowed where these clearly referred to relative rate of the processes; 5) object was counted when it referred to the generic nature of the items; 6) natural was allowed since it referred to unmanufactured objects.