Intelligence 38 (2010) 193–201

Contents lists available at ScienceDirect

Intelligence

On the relationship between fluid intelligence, gesture production, and brain structure ☆

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A R T I C L E I N F O

Article history:
Received 2 June 2009
Received in revised form 13 August 2009
Accepted 3 November 2009
Available online 20 November 2009

Keywords:
Fluid intelligence
Structural MRI
Gesture production
Geometric analogies
Analogical thinking
Average and high fluid intelligence
Cortical thickness
Representational and movement gestures
Brain morphometry

A B S T R A C T

Individuals scoring high in fluid intelligence tasks generally perform very efficiently in problem solving tasks and analogical reasoning tasks presumably because they are able to select the task-relevant information very quickly and focus on a limited set of task-relevant cognitive operations. Moreover, individuals with high fluid intelligence produce more representational hand and arm gestures when describing a geometric analogy task than individuals with average fluid intelligence. No study has yet addressed the relationship between intelligence, gesture production, and brain structure, to our knowledge. That was the purpose of our study. To characterize the relation between intelligence, gesture production, and brain structure we assessed the frequency of representational gestures and cortical thickness values in a group of adolescents differing in fluid intelligence. Individuals scoring high in fluid intelligence showed higher accuracy in the geometric analogy task and produced more representational gestures (in particular more movement gestures) when explaining how they solved the task and showed larger cortical thickness values in some regions in the left hemisphere (namely the pars opercularis, superior frontal, and temporal cortex) than individuals with average fluid intelligence. Moreover, the left pars opercularis (a part of Broca's area) and left transverse temporal cortex showed larger cortical thickness values in participants who produced representational and in particular movement gestures compared to those who did not. Our results thus indicate that cortical thickness of those brain regions is related to both high fluid intelligence and the production of gestures. Results are discussed in the gestures-as-simulated-action framework that states that gestures result from simulated perception and simulated action that underlie embodied language and mental imagery.

1. Introduction

The human cognitive system is a highly-evolved collection of neural structures and processes that are routinely used to accomplish the demands and challenges of our everyday lives. However, the cognitive system reveals individual differences. For example, it is well-known that individuals with high levels of intelligence generally perform very efficiently in problem solving tasks (Vernon, 1983). Analogical reasoning is a

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doi:10.1016/j.intell.2009.11.001

prototypical task that has been used in different psychometric tests measuring intelligence, in particular *fluid intelligence* (e.g., Raven, 1958). Individuals with high fluid intelligence are assumed to select the task-relevant information very quickly and to focus on a limited set of task-relevant cognitive operations (e.g., Vernon, 1983). Thus, they solve analogy tasks more accurately and faster than individuals with lower fluid intelligence (van der Meer, 1996; van der Meer et al., 2009).

Individuals with high fluid intelligence also produce more representational hand and arm gestures[1] than do individuals with average fluid intelligence, when their gestures are measured during their spoken explanations of how they solved a previous geometric analogy task (Sassenberg et al., submitted for publication). More specifically, their representational gestures often indicated movement of imagined objects or of how these objects were moved. Similarly, children with better rather than poorer spatial skills also gesture more about movements in their subsequent explanations (Ehrlich, Levine & Goldin-Meadow, 2006). The relationship between gestures and a cognitive ability such as fluid intelligence is consistent with the gestures-as-simulated-action (GSA) framework (Hostetter & Alibali, 2008). According to this theory, gestures result from simulated perception and simulated action that underlie embodied language and mental imagery. Simulated perception and simulated action are formats of mental representations within the framework of embodied cognition (Barsalou, 1999; Barsalou, 2008; Glenberg, 1997; Glenberg & Kaschak, 2002; Jeannerod, 2001). According to the GSA framework, simulated actions become overt gestures when their activation strength exceeds a current gesture threshold, especially during speaking. For instance, a gesture is more likely to be produced when individuals talk about something that involves very active representations, such as mental transformation, compared to less active representations like retrieving an image from memory (cf., Cornoldi & Vecchi, 2003). Within the GSA framework, gestures mostly accompany speech because hand and mouth actions are assumed to share the same underlying control system located in Broca's area in the brain (Gentilucci & Dalla Volta, 2008). Moreover, there is a rapid spreading from motor plans to executed articulatory movements for speech, thereby presumably facilitating the spread of motor plans to executed hand movements for gesture (Hostetter & Alibali, 2008). Activity of Broca's area, known for its role in language processing, has also been linked to control components of gesture comprehension and gesture production (Gentilucci & Dalla Volta, 2008; Johnson-Frey, Newman-Norlund & Grafton, 2005; Leiguarda & Marsden, 2000; Skipper, Goldin-Meadow, Nusbaum & Small, 2007; Villarreal et al., 2008). The activity of Broca's area in spoken language comprehension is also influenced by the presence and content of co-speech gestures (Holle, Gunter, Rüschemeyer, Hennenlotter, & Iacoboni, 2008; Skipper et al., 2007; Willems & Hagoort, 2007; Willems, Özyürek, & Hagoort, 2007). For example, Broca's area shows increased activity when speech-accompanying gestures are not coherent with the speech content (Willems et al., 2007).

Broca's area might also be of relevance concerning the possible neural substrate for a relationship between language, gesture, and fluid intelligence. A recent study by Lerch et al. (2006) investigated the relationship between general intelligence and cortical thickness. Interestingly, participants who showed high levels of intelligence also demonstrated larger cortical thickness correlations between the pars opercularis (Brodmann area [BA] 44, a part of Broca's area) and other frontal and parietal brain areas that are also involved in human gesturing. However, in that study, gesture frequency of individuals was not assessed.

The prominent role of (left) inferior frontal and parietal brain regions as core regions of human intelligence has been highlighted by several functional and structural brain imaging studies (e.g., Goel, Gold, Kapur, & Houle, 1998; Haier, 2009; Haier, Jung, Yeo, Head, & Alkire, 2004; Lee et al., 2006; Narr et al., 2007; Shaw et al., 2006; for review see Jung & Haier, 2007). Note that functional imaging studies show task-related changes in cerebral oxygenation while participants repeatedly solve a certain kind of task, and differences in brain structure emphasize specialized brain regions in certain groups of participants. Most studies emphasize that intelligence modulates a widespread fronto-parietal network and report on a positive correlation of intelligence and cortical thickness (for details see Discussion).

However, to our knowledge, no study has yet addressed the relationship between intelligence, gesture production, and brain structure. Therefore, in the present study, we aimed to determine the relationship between fluid intelligence, performance in an analogical reasoning task, gesture production while explaining the task solution afterwards, and brain structure (cortical thickness). Given that (i) gesture processing is mediated by Broca's area in the left inferior frontal cortex, (ii) participants with high fluid intelligence produce more representational gestures in explanations of an analogical reasoning task than those with average fluid intelligence, and (iii) fluid intelligence is strongly related to the fronto-parietal cortices, we hypothesized that Broca's area is a key structure for both fluid intelligence and gesture production. Such findings would have important implications about brain development, intelligence, and the precise functions of Broca's area.

2. Method

2.1. Psychometric tests

Twenty-eight participants (males, right-handed, age 17.2 ± 0.5 years) were screened for levels of fluid intelligence using the Raven Advanced Progressive Matrices test (RAPM, Heller, Kratzmeier & Lengfelder, 1998; Raven, 1958). In addition, we applied the d2 test for the assessment of attention performance (Brickenkamp & Zillmer, 1998). The subpart “verbal knowledge” of the *Intelligenz-Struktur-Test 2000 R* was also applied as a control test to assess crystallized intelligence (IST, Amthauer, Brocke, Liepmann, & Beauducel, 2001).

Based on their RAPM scores, participants were assigned to a high fluid intelligence group (RAPM = 130.8 ± 7.8, N = 17) and an average fluid intelligence group (RAPM = 104.2 ± 7.2,

[1] Representational gestures are movements that express semantic or pragmatic content, often in close relationship to the co-occurring speech (“iconic”, “metaphoric”, and “deictic” gestures according to McNeill, 1992). Non-representational gestures would be, for example, rhythmic movements like “beats” (McNeill, 1992).