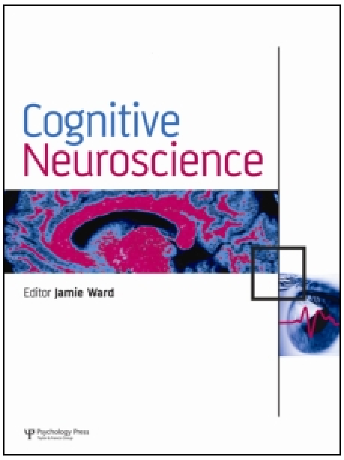
This article was downloaded by: *[University of California, Los Angeles]*
On: *7 June 2010*
Access details: *Access Details: [subscription number 918974475]*
Publisher *Psychology Press*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Cognitive Neuroscience
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t909559412

Does the PFC model of analogy account for decision making, problem solving, reasoning, flexibility, adaptability, and even creativity?

Joaquin Barutta[a]; Raphael Guex[b]; Agustín Ibáñez[c]
[a] Italian Hospital University, Buenos Aires, Argentina [b] University of Geneva, Geneva, Switzerland [c] Institute of Cognitive Neurology, (INECO), Favaloro University, National Scientific and Technical Research Council (CONICET), Buenos Aires, Argentina, and Universidad Diego Portales, Santiago, Chile

Online publication date: 07 June 2010

To cite this Article Barutta, Joaquin , Guex, Raphael and Ibáñez, Agustín(2010) 'Does the PFC model of analogy account for decision making, problem solving, reasoning, flexibility, adaptability, and even creativity?', Cognitive Neuroscience, 1: 2, 142 — 143
To link to this Article: DOI: 10.1080/17588921003786580
URL: http://dx.doi.org/10.1080/17588921003786580

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

functions as a domain-general, biasing mechanism that sculpts the representational response space (Frith, 2000), focusing attention on certain aspects or features of a representation during analogical reasoning, while ignoring others. Such a conceptualization of the PFC may allow for explicit predictions regarding the extent of the involvement of this region depending on the type of analogical reasoning. According to this approach, PFC might be involved in analogies that are based on strong preexisting knowledge of abstract structural relationships in the source and target domains. In such cases, biasing the response space would allow for focus only on the relevant aspects of these relationships for a successful analogical mapping between the source and target domains. In contrast, PFC regions may not be involved to the same extent for analogies that are not based on explicit preexisting knowledge and which—if successful—might lead to new discoveries. In such cases, biasing the response space may be counterproductive, given that one may not know in advance which relationships will become of optimal behavioral relevance (see Chrysikou & Thompson-Schill, in press; Thompson-Schill, Ramscar, & Chrysikou, 2009).

We argue that such an approach to PFC offers a neural framework for analogical reasoning that is able to account for both types of analogy, which may further our understanding of analogical transfer (or its failure) in real-life circumstances.

ACKNOWLEDGMENTS

This work was supported by NIMH grant R21MH083029 and NIDCD grant R01DC009209 to Sharon L. Thompson-Schill.

* * *

Does the PFC model of analogy account for decision making, problem solving, reasoning, flexibility, adaptability, and even creativity?

Joaquín Barutta[1], Raphael Guex[2], and Agustín Ibáñez[3]

[1]*Italian Hospital University, Buenos Aires, Argentina*

[2]*University of Geneva, Geneva, Switzerland*

[3]*Institute of Cognitive Neurology, (INECO), Favaloro University, National Scientific and Technical Research Council (CONICET), Buenos Aires, Argentina, and Universidad Diego Portales, Santiago, Chile*

E-mail: aibanez@neurologiacognitiva.org

DOI: 10.1080/17588921003786580

Abstract: From everyday cognition to scientific discovery, analogical processes play an important role: bringing connection, integration, and interrelation of information. Recently, a PFC model of analogy has been proposed to explain many cognitive processes and integrate general functional properties of PFC. We argue here that analogical processes do not suffice to explain the cognitive processes and functions of PFC. Moreover the model does not satisfactorily integrate specific explanatory mechanisms required for the different processes involved. Its relevance would be improved if fewer cognitive phenomena were considered and more specific predictions and explanations about those processes were stated.

Speed proposes a novel PFC model of analogical processing. This model explains analogical processes as a progressive integration from posterior to more anterior areas of PFC, during which the information processing increases in abstractness and complexity. The fronto-striatal circuits would bring the basis for analogy formation and persistence, sustained by learning and prediction of reward/punishment. The model is discussed in relation to other approaches to PFC and also to several processes involved, such as explicit and implicit processing, long vs. short-term representations, and cognitive control. More importantly, this model is presented as a useful tool for integrating the multiple functions of PFC in order to understand complex behaviors, such as decision making, problem solving, reasoning, flexibility, adaptability, and even creativity.

In spite of the main merit of this work, which lies in an effort to integrate the different roles of PFC and the analogical processes in order to understand complex behaviors, there are several caveats that raise doubts about the model's usefulness.

Although analogy would be a very important factor in wide-ranging cognitive processes, it is hard to imagine how a general cognitive skill such as analogy could be enough to explain as many cognitive processes as proposed by Speed. Would the same analogical model explain decision making, reasoning, creativity, and other very disparate processes? How is it possible for such a model to achieve this goal? Is there an identical neuronal substrate for all these cognitive processes? No precise description or insight on these main issues can be found in the paper. In the same vein, those complex

Downloaded By: [University of California, Los Angeles] At: 19:25 7 June 2010

cognitive skills usually involve a conjugation of several processes (e.g., decision making can engage reversal learning and inhibition, risk-taking, emotion, executive function, and working memory, and some of those skills are known to be processed in other areas than the PFC; Dunn, Dalgleish, & Lawrence, 2006). No clear pathways that explain the sufficiency of analogy to account for such disparate cognitive processes are addressed in the PFC analogy model.

Moreover, the model doesn't sufficiently specify the kinds of analogies involved in such cognitive processes. Even though analogical explanation, analogical description, and analogical reasoning share a common characteristic (all make use of analogies), the kinds of information they provide are substantially different (Copi, 1994; Gamut, 1991). In fact, in spite of the well-known relevance of analogical reasoning in cognitive processes such as decision making or problem solving, the paper seems to specifically focus on analogical explanation and description. This is also apparent in the examples provided by the author.

Today it is widely accepted that complex cognition recruits large and relatively specific networks, including but also going beyond the PFC, and with very detailed cognitive properties. This is especially relevant when considering decision making (Frith & Singer, 2008), reasoning (Reijneveld, Ponten, Berendse, & Stam, 2007), creativity (Yeats & Yeats, 2007), or problem solving (Unterrainer & Owen, 2006). The proposed model does not fit as an explanatory mechanism of the neurocognitive functions required to address such different cognitive and neurophysiological processes. If no specific behavioral or neurophysiological predictions can be stated for each cognitive phenomenon addressed by this model, the extreme extension of the phenomena considered by the model becomes an enormous difficulty instead of being advantageous over alternative PFC explanations.

In brief, although Speed's proposal is novel and interesting, it sounds too ambitious and at the same time lacks the wide range of model predictions and explanations expected to account for such a variety of phenomena. Possibly, a model improvement would consist in a less ambitious range of cognitive phenomena and, simultaneously, the development of a more specific set of predictions and explanations.

ACKNOWLEDGMENTS

Supported by the CONICET career grant to Agustin Ibáñez.

* * *

What role for the anterior cingulate in analogical reasoning?

Michael W. O'Boyle
Department of Human Development and Family Studies, Texas Tech University, Lubbock, TX 7940, USA
E-mail: michael.oboyle@ttu.edu

DOI: 10.1080/17588921003802064

Abstract: While prefrontal and frontal cortex of the brain are well documented to mediate many executive functions, including creativity, flexibility, and adaptability, the anterior cingulate cortex (ACC) is known to be involved in error detection and conflict resolution, and is crucial to reward-based learning. A case is made for the notion that any neural model of analogical reasoning must incorporate the critical (and specialized) contributions of the ACC.

In her target article, Ann Speed does an admirable job of outlining a model designed to capture the neural circuitry underlying analogical reasoning in the brain. In particular, she suggests that different neurons along the anterior–posterior axis of the prefrontal cortex (PFC) are differentially sensitive to the abstractness and relatedness of the informational components comprising analogies, and that the persistence of the representations used for analogy solution is mediated by fronto-parietal neural circuits that are sensitive to environmental consequences (i.e., their potential for success/reward or failure/punishment).

One aspect of the model that seems to have been overlooked, however, is the engagement of the anterior cingulate cortex (ACC) during higher-order cognition. Note that considerable research is being done on this brain region (Brodmann area 32 and others), which has revealed a crucial role both anatomically and behaviorally for the ACC in the performance of a variety of higher-order cognitive tasks: contributions that would presumably extend to the analogical reasoning process.

At the anatomical level it is well documented that bilateral premotor and dorsolateral PFC are highly interconnected and that each of these regions projects directly to the ACC, which in turn is highly interconnected with virtually all other frontal areas of the brain (Petrides & Pandya, 1999). Moreover at the behavioral level, the ACC is known to mediate and facilitate the online monitoring of performance primarily through error checking and conflict resolution

Downloaded By: [University of California, Los Angeles] At: 19:25 7 June 2010

cortices as a function of responses to subordinate (e.g., individual representations of the number 1), ordinate (e.g., the concept of the number 1), and superordinate (e.g., the concept of prime numbers, real numbers, integers, etc.) stimuli in progressively more complex problems could test this hypothesis.

Regarding the location of semantic knowledge representation question raised by Badre, an area of research that seems lacking in the PFC literature is in the development of knowledge: from childhood to adult (which exists in the analogy literature to an extent, e.g., Crone et al., 2009), from novice to expert, and from immediately post-injury to years out. Such analysis could be very instructive, and should complement the many snapshots of functioning we have now. For example, Sylvester & Shimamura (2002) examine the semantic categorization abilities of several frontal patients who average 11 years post-injury. They found that patients group common animals in the same way that an uninjured age-controlled group does. However, if the current theory is correct, 11 years is plenty of time for patients to have reacquired these categorical representations in undamaged areas of PFC. Thus, testing to see whether this categorization changes over time post-injury could be instructive.

Badre also raises the issue that striatal circuits may not be necessary for the development of relational knowledge. However, one finding from the education literature is that the way knowledge is learned in the classroom (i.e., by being told) can produce “inert” knowledge. That is, while the student may be able to restate the concept, he is unable to transfer it to a novel situation or problem (Bransford, Sherwood, Vye, & Rieser, 1986; Smith, Ford, & Kozlowski, 1997). Imaging studies comparing semantic knowledge that can only be restated vs. semantic knowledge that can be transferred analogically will elucidate whether the type of knowledge addressed by the current proposal is different from that discussed by Badre.

There are certainly many empirical data to collect in order to determine the viability of the current proposal. However, this account does raise some important questions for current theoretical perspectives regarding the physical mechanisms underlying those proposals. As I have argued elsewhere (Speed, 2008), there is a need to pay increasing attention to the actual physical mechanisms that underlie theoretical accounts of PFC function (see also, Hazy, Frank, & O’Reilly, 2006; O’Reilly & Frank, 2006). Irrespective of the ultimate fate of the current proposal, I hope that empirical tests pitting it against other perspectives, and additional physiologically based computational modeling efforts, will result in a more complete understanding of the physical mechanisms underlying PFC function.

Downloaded By: [University of California, Los Angeles] At: 19:25 7 June 2010

References from the Discussion Paper, the Commentaries, and the Reply

Anolli, L., Antonietti, A., Cantoia, M., & Crisafulli, L. (2001). Accessing source information in analogical problem solving. *Quarterly Journal of Experimental Psychology*, *54A*, 237–261.

Antonietti, A. (2001). *Analogical discoveries: Identifying similarities to solve problems*. Rome: Carocci.

Antonietti, A., & Gioletta, M. A. (1995) Individual differences in analogical problem solving. *Personality and Individual Differences*, *18*, 611–619.

Ashby, F. G., & Ennis, J. M. (2006). The role of the basal ganglia in category learning. In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 46, pp.1–36). New York: Elsevier.

Ashby, F. G., Ennis, J. M., & Spiering, B. J. (2007). A neurobiological theory of automaticity in perceptual categorization. *Psychological Review*, *114*(3), 632–656.

Au, T. K., Chan, C. K. K., Chan, T.-K., Cheung, M. W. L., Ho, J. Y. S., & Ip, G. W. M. (2008). Folkbiology meets microbiology: A study of conceptual and behavioral change. *Cognitive Psychology*, *57*, 1–19.

Aziz-Zadeh, L., Kaplan, J. T., & Iacoboni, M. (2009). Aha! The neural correlates of verbal insight solutions. *Human Brain Mapping*, *30*, 908–916.

Badger, J. R., & Shapiro, L. R. (2010). The shift from perceptual to category induction is independent of featural distraction. *Manuscript submitted for publication.*

Badre, D. (2008). Cognitive control, hierarchy, and the rostro-caudal organization of the frontal lobes. *Trends in Cognitive Science*, *12*(5), 193–200.

Badre, D., & D’Esposito, M. (2007). Functional magnetic resonance imaging evidence for a hierarchical organization of the prefrontal cortex. *Journal of Cognitive Neuroscience*, *19*(12), 2082–2099.

Badre, D., Hoffman, J., Cooney, J. W., & D’Esposito, M. D. (2009). Hierarchical cognitive control deficits following damage to the human frontal lobe. *Nature Neuroscience*, *12*(4), 515–522.

Bar, M. (2007). The proactive brain: Using analogies and associations to generate predictions *Trends in Cognitive Sciences*, *11*(7), 280–289.

Downloaded By: [University of California, Los Angeles] At: 19:25 7 June 2010

Barbas, H. (2000). Connections underlying the synthesis of cognition, memory, and emotion in primate prefrontal cortices. *Brain Research Bulletin*, *52*, 319–330.

Bechara, A., & Damasio, A. R. (2005). The somatic marker hypothesis: A neural theory of economic decision. *Games and Economic Behavior*, *52*, 336–372.

Boroojerdi, B., Phipps, M., Kopylev, L., Wharton, C. M., Cohen, L. G., & Grafman, J. (2001). Enhancing analogic reasoning with rTMS over the left prefrontal cortex. *Neurology*, *56*, 526–528.

Botvinick, M. M. (2008). Hierarchical models of behavior and prefrontal function. *Trends in Cognitive Sciences*, *12*(5), 201–208.

Bransford, J. D., Sherwood, R., Vye, N. J., & Rieser, J. (1986). Teaching thinking and problem solving. *American Psychologist*, *41*, 1078–1089.

Bulloch, M. J., & Opfer, J. E. (2009). What makes relational reasoning smart? Revisiting the perceptual-to-relational shift in the development of generalization. *Developmental Science*, *12*(1), 114–122.

Bunge, S. A., Wendelken, C., Badre, D., & Wagner, A. D. (2005). Analogical reasoning and prefrontal cortex: Evidence for separable retrieval and integration mechanisms. *Cerebral Cortex*, *15*, 239–249.

Bush, G., Vogt, B. A., Holmes, J., Dale, A. M., Greve, D., Jenike, M. A., et al. (2002). Dorsal anterior cingulate cortex: A role in reward-based decision making. *Proceedings of the National Academy of Sciences of the United States of America*, *99*(1), 523–528.

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience*, *12*(1), 1–47.

Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. N., Noll, D., & Cohen J. D. (1998). Anterior cingulate cortex, error detection and the on-line monitoring of performance. *Science*, *280*(5364), 747–749.

Catrambone, R., & Holyoak, K. J. (1989). Overcoming contextual limitations on problem-solving transfer. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 1147–1156.

Chow, T. W., & Cummings, J. L. (2007). Frontal-subcortical circuits. In B. L. Miller & J. L. Cummings (Eds.), *The human frontal lobes: Functions and disorders* (2nd ed., pp. 25–43). New York: Guilford Press.

Christoff, K., & Gabrieli, J. D. E. (2000). The frontopolar cortex and human cognition: Evidence for a rostrocaudal hierarchical organization within the human prefrontal cortex. *Psychobiology*, *28*, 168–186.

Christoff, K., Geddes, L. M. T., & Gabrieli, J. D. E. (2001a). Rostrolateral prefrontal cortex involvement in evaluating self-generated information. *NeuroImage*, *13*, S649.

Christoff, K., & Keramatian, K. (2007). Abstraction of mental representations: Theoretical considerations and neuroscientific evidence. In S. A. Bunge & J. D. Wilson (Eds.), *Perspectives on rule-guided behavior* (pp. 107–126), Oxford, UK: Oxford University Press.

Christoff, K., Keramatian, K., Gordon, A. M., Smith, R., & Madler, B. (2009). Prefrontal organization of cognitive control according to levels of abstraction. *Brain Research*, *1286*, 94–105.

Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., Holyoak, K. J., et al. (2001b). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. *NeuroImage*, *14*(5), 1136–1149.

Christoff, K., Ream, J. M., Geddes, L. M. T., & Gabrieli, J. D. E. (2003). Evaluating self-generated information: Anterior prefrontal contributions to human cognition. *Behavioral Neuroscience*, *117*(6), 1161–1168.

Chrysikou, E. G., & Thompson-Schill, S. L. (in press). Dissociable brain states linked to common and creative object use. *Human Brain Mapping*.

Cohen, N. J., Eichenbaum, H., & Poldrack, R. A. (1997). Memory for items and memory for relations in the procedural/declarative memory framework. *Memory*, *5*, 131–178.

Constantinidis, C., Franowicz, M. N., & Goldman-Rakic, P. S. (2001). The sensory nature of mnemonic representation in the primate prefrontal cortex. *Nature Neuroscience*, *4*(3), 311–316.

Copi, I. M. (1994). *Introduction to logic* (9th ed.). New York: Macmillan.

Cormier, S. M. (1987). The structural processes underlying transfer of training. In S. M. Cormier & J. D. Hagman (Eds.), *Transfer of learning: Contemporary research and applications* (pp. 152–182). San Diego, CA: Academic Press.

Crone, E. A., Wendelken, C., van Leijenhorst, L., Honomichl, R. D., Christoff, K., & Bunge, S. A. (2009). Neurocognitive development of relational reasoning. *Developmental Science*, *12*(1), 55–66.

Cummings, J. L., & Miller, B. L. (2007). Conceptual and clinical aspects of the frontal lobes. In B. L. Miller & J. L. Cummings (Eds.), *The human frontal lobes: Functions and disorders* (2nd ed., pp. 12–21). New York: Guilford.

Damasio, H., Tranel, D., Grabowski, T., Adolphs, R., & Damasio, A. (2004). Neural systems behind word and concept retrieval. *Cognition*, *92*(1–2), 179–229.

Duncan, J. (2005). Task models in prefrontal cortex. In U.Mayr, E.Awh, S. W. Keele, & M. I. Posner (Eds.), *Developing individuality in the human brain: A tribute to Michael I. Posner* (pp. 87–108). Washington, DC: American Psychological Association.

Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neuroscience*, *23*, 475–483.

Dunn, B. D., Dalgleish, T., Lawrence, A. D. (2006). The somatic marker hypothesis: A critical evaluation. *Neuroscience & Biobehavioral Reviews*, *30*(2), 239–271.

Eliasmith, C., & Thagard, P. (2001). Integrating structure and meaning: A distributed model of analogical mapping. *Cognitive Science*, *25*, 245–286.

Falkenhainer, B., Forbus, K. D., & Gentner, D. (1989). The structure mapping engine: Algorithm and examples. *Artificial Intelligence*, *41*, 1–63.

Frank, M. J. (2005). Dynamic dopamine modulation in the basal ganglia: A neurocomputational account of cognitive deficits in medicated and nonmedicated Parkinsonism. *Journal of Cognitive Neuroscience*, *17*(1), 51–72.

Freedman, D. J., Riesenhuber, M., Poggio, T., & Miller, E. K. (2001). Categorical representation of visual stimuli in the primate prefrontal cortex. *Science*, *291*, 312–316.

Freedman, D. J., Riesenhuber, M., Poggio, T., & Miller, E. K. (2002). Visual categorization and the primate prefrontal cortex: Neurophysiology and behavior. *Journal of Neurophysiology*, *88*, 929–941.

Freedman, D. J., Riesenhuber, M., Poggio, T., & Miller, E. K. (2003). A comparison of primate prefrontal and inferior temporal cortices during visual categorization. *Journal of Neuroscience*, *23*(12), 5235–5246.

Downloaded By: [University of California, Los Angeles] At: 19:25 7 June 2010

Frith, C. (2000). The role of dorsolateral prefrontal cortex in the selection of action as revealed by functional imaging. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes* (pp. 549–565). Cambridge, MA: MIT Press.

Frith, C. D., Singer, T. (2008). The role of social cognition in decision-making. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*, 3875–3886.

Fuster, J. M. (1997). *The prefrontal cortex: Anatomy, physiology, and neuropsychology of the frontal lobe* (3rd ed.). Philadelphia: Lippincott-Raven.

Fuster, J. M. (2006). The cognit: A network model of cortical representation. *International Journal of Psychophysiology*, *60*, 125–132.

Gamut, L. T. F. (1991). *Logic, language and meaning*. Chicago: University of Chicago Press.

Geake, J. G., & Hansen, P. C. (2005). Neural correlates of intelligence as revealed by fMRI of fluid analogies. *NeuroImage*, *26*(2), 555–564.

Gelman, S. A. (2003). *The essential child: Origins of essentialism in everyday thought*. New York: Oxford University Press.

Gentner, D. (1983). Structure mapping: A theoretical framework for analogy. *Cognitive Science*, *7*, 155–170.

Gentner, D. (1989). The mechanisms of analogical mapping. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 199–241). New York: Cambridge University Press.

Gentner, D., Bowdle, B., Wolff, P., & Boronat, C. (2001). Metaphor is like analogy. In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.), *The analogical mind: Perspectives from cognitive science*. Cambridge, MA: MIT Press.

Gentner, D., & Markman, A. B. (1997). Structure mapping in analogy and similarity. *American Psychologist*, *52*, 45–56.

Gentner, D., & Toupin, C. (1986). Systematicity and surface similarity in the development of analogy. *Cognitive Science*, *10*, 277–300.

Ghodsian, D., Bjork, R. A., & Benjamin, A. S. (1997). Evaluating training *during* training: Obstacles and opportunities. In M. A. Quinones & A. Ehrenstein (Eds.), *Training for a rapidly changing workplace: Applications of psychological research* (pp. 63–88). Washington, DC: American Psychological Association.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology*, *12*, 306–355.

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology*, *15*, 1–38.

Goldman-Rakic, P. S. (1987). Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. *Handbook of Physiology*. Bethesda, MD: American Psychological Society.

Green, A. E., Fusgelsang, J. A., Kraemer, D. J. M., Shamosh, N. A., & Dunbar, K. N. (2006). Frontopolar cortex mediates abstract integration in analogy. *Brain Research*, *1096*, 125–137.

Green, A. E., Kraemer, D. J. M., Fugelsang, J. A., Gray, J. R., & Dunbar, K. N. (2010). Connecting long distance: Semantic distance in analogical reasoning modulates frontopolar cortex activity. *Cerebral Cortex*, *20*, 70–76.

Harrington, D. L., Haaland, K., & Knight, R. (1998). Cortical networks underlying mechanism of time perception. *Journal of Neuroscience*, *18*, 1085–1095.

Hazy, T. E., Frank, M. J., & O'Reilly, R. C. (2006). Banishing the homunculus: Making working memory work. *Neuroscience*, *139*, 105–118.

Hofstadter, D. R. (1995). *Fluid concepts and creative analogies*. New York: Basic Books.

Hofstadter, D. R. (2001). Epilogue: Analogy as the core of cognition. In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.), *The analogical mind: Perspectives from cognitive science* (pp. 499–538). Cambridge, MA: MIT Press.

Holyoak, K. J., & Thagard, P. (1997). The analogical mind. *American Psychologist*, *52*, 35–44.

Huey, E. D., Krueger, F., & Grafman, J. (2006). Representations in the human prefrontal cortex. *Current Directions in Psychological Science*, *15*, 167–171.

Hummel, J. E., & Holyoak, K. J. (1997). Distributed representations of structure: A theory of analogical access and mapping. *Psychological Review*, *104*, 427–466.

Hummel, J. E., & Holyoak, K. J. (2003). A symbolic-connectionist theory of relational inference and generalization. *Psychological Review*, *110*, 220–264.

Keane, M., Ledgeway, T., & Duff, S. (1994). Constraints on analogical mapping: A comparison of three models. *Cognitive Science*, *18*, 387–438.

Kelly, A. M. C., & Garavan, H. (2005). Human functional neuroimaging of brain changes associated with practice. *Cerebral Cortex*, *15*, 1089–1102.

Koechlin, E., Corrado, G., Pietrini, P., & Grafman, J. (2000). Dissociating the role of the medial and lateral anterior prefrontal cortex in human planning. *Proceedings of the National Academy of Sciences of the United States of America*, *97*(13), 7651–7656.

Koechlin, E., & Hayfil, A. (2007). Anterior prefrontal function and the limits of human decision-making. *Science*, *318*, 594–598.

Koechlin, E., Ody, C., & Kouneiher, F. (2003). The architecture of cognitive control in human prefrontal cortex. *Science*, *302*, 1181–1185.

Kokinov, B. N., & Petrov, A. A. (2001). Integrating memory and reasoning in analogy-making: The AMBR model. In D. Genter, K. J. Holyoak, & B. N. Kokinov (Eds.), *The analogical mind: Perspectives from cognitive science* (pp. 59–124). Cambridge, MA: MIT Press.

Kouneiher, F., Charron, S., & Koechlin, E. (2009). Motivation and cognitive control in the human prefrontal cortex. *Nature Neuroscience*, *12*(7), 939–945.

Kramer, J. H., & Quitania, L. (2007). Bedside frontal lobe testing. In B. L. Miller & J. L. Cummings (Eds.), *The human frontal lobes: Functions and disorders* (2nd ed., pp. 279–291). New York: Guilford.

Krawczyk, D. C., Morrison, R. G., Viskontas, I., Holyoak, K. J., Chow, T. W., Mendez, M. F., et al. (2008). Distraction during relational reasoning: The role of prefrontal cortex in interference control. *Neuropsychologia*, *46*, 2020–2032.

Kroger, J. K., Saab, F. W., Fales, C. I., Bookheimer, S. Y., Cohen, M. S., & Holyoak, K. J. (2002). Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: A parametric study of relational complexity. *Cerebral Cortex*, *12*, 477–485.

Kroger, J. K., Speed, A., Anderson, J. P., Mikkelsen, E. J., Spring, D. K., & Polsky, A. L. (2007, October). *An ERP study of analogical reasoning*. Paper presented at the 47th Annual Meeting of the Society for Psychophysiological Research, Savannah, GA.

Downloaded By: [University of California, Los Angeles] At: 19:25 7 June 2010

Krueger, F., Barbey, A. K., & Grafman, J. (2009). The medial prefrontal cortex mediates social event knowledge. *Trends in Cognitive Sciences*, *13*, 103–109.

Leech, R., Mareschal, D., & Cooper, R. P. (2008). Analogy as relational priming: A developmental and computational perspective on the origins of a complex cognitive skill. *Behavioral and Brain Sciences*, *31*, 357–378.

Leon, M. I., & Shadlen, M. N. (2003). Representation of time by neurons in the posterior parietal cortex of the macaque. *Neuron*, *38*, 317–327.

Luo, Q., Perry, C., Peng, D., Jin, Z., Xu, D., Ding, G., et al. (2003). The neural substrate of analogical reasoning: An fMRI study. *Cognitive Brain Research*, *17*, 527–534.

Martin, A., & Chao, L. L. (2001). Semantic memory and the brain: Structure and processes. *Current Opinion in Neurobiology*, *11*(2), 194–201.

Mikkelsen, E. J., Speed, A., Anderson, J. P., Spring, D. K., Polsky, A. L., & Kroger, J. K. (2010 *Manuscript submitted for publication.*). Dissociated processing of representational structure and surface features in an analogical reasoning task: An ERP study.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Reviews of Neuroscience*, *24*, 167–202.

Miller, E. K., Erickson, C. A., & Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *Journal of Neuroscience*, *16*, 5154–5167.

Miller, E. K., Nieder, A., Freedman, D. J., & Wallis, J. D. (2003). Neural correlates of categories and concepts. *Current Opinion in Neurobiology*, *13*, 198–203.

Mitchell, M. M. (1993). *Analogy-making as perception*. Cambridge, MA: MIT Press.

Nieder, A., & Miller, E. K. (2004). A parieto-frontal network for visual numerical information in the monkey. *Procedings of the National Academy of Sciences of the United States of America*, *101*, 7457–7462.

Nishijo, H., Yamamoto, Y., Ono, T., Uwano, T., Yamashita, J., & Yamashima, T. (1997). Single neuron responses in the monkey anterior cingulate cortex during visual discrimination. *Neuroscience Letters*, *227*, 79–82.

Novick, L. R. (1988). Analogical transfer, problem similarity, and expertise. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *14*, 510–520.

Novick, L. R., & Holyoak, K. J. (1991). Mathematical problem solving by analogy. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*, 398–415.

O'Boyle, M. W., Cunnington, R., Silk, T., Vaughan, D., Jackson, G., Syngeniotis, A., et al. (2005). Mathematically gifted male adolescents activate a unique brain network during mental rotation. *Cognitive Brain Research*, *25*, 583–587.

Onoe, H., Komori, M., Onoe, K., Takechi, H., Tsukada, H., & Watanabe, Y. (2001). Networks recruited for time perception: A monkey positron emission tomography (PET) study. *NeuroImage 13*, 37–45.

O'Reilly, R. C., & Frank, M. J. (2006). Making working memory work: A computational model of learning in the prefrontal cortex and basal ganglia. *Neural Computation*, *18*, 283–328.

O'Reilly, R. C., Noelle, D. C., Braver, T. S., & Cohen, J. D. (2002). Prefrontal cortex and dynamic categorization tasks: Representational organization and neuromodulatory control. *Cerebral Cortex*, *12*, 246–257.

Petrides, M., & Pandya, D. N. (1999). Dorsolateral prefrontal cortex: Comparative cytoarchitectonic analysis in the human and the macaque brain and corticocortical connection patterns. *European Journal of Neuroscience*, *11*(3), 1011–1036.

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

Qiu, J., Li, H., Chen, A., & Zhang, Q. (2008). The neural basis of analogical reasoning: An event-related potential study. *Neuropsychologia*, *46*, 3306–3013.

Rainer, G., & Miller, E. K. (2000). Effects of visual experience on the representation of objects in the prefrontal cortex. *Neuron*, *27*, 179–189.

Ramnani, N., & Owen, A. M. (2004). Anterior prefrontal cortex: Insights into function from anatomy and neuroimaging. *Nature Reviews Neuroscience*, *5*, 184–194.

Rao, S. M., Mayer, A. R., & Harrington, D. L. (2001). The evolution of brain activation during temporal processing. *Nature Neuroscience*, *4*, 317–323.

Reijneveld, J. C., Ponten, S. C., Berendse, H. W., & Stam, C. J. (2007). The application of graph theoretical analysis to complex networks in the brain. *Clinical Neurophysiology*, *118*(11), 2317–2331.

Reynolds, J. R., & O'Reilly, R. C. (2009). Developing PFC representations using reinforcement learning. *Cognition*, *113*(3), 281–292.

Richland, L. E., Morrison, R. G., & Holyoak, K. J. (2006). Children's development of analogical reasoning: Insights from scene analogy problems. *Journal of Experimental Child Psychology*, *94*, 249–273.

Ross, B. H. (1987). This is like that: The use of earlier problems and the separation of similarity effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 629–639.

Ross, B. H. (1989). Distinguishing types of superficial similarities: Different effects on the access and use of earlier problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 456–468.

Rougier, N. P., Noelle, D. C., Braver, T. S., Cohen, J. D., & O'Reilly, R. C. (2006). Prefrontal cortex and flexible cognitive control: Rules without symbols. *Proceedings of the National Academy of Sciences of the United States of America*, *102*, 7338–7343.

Sandkühler, S., & Bhattacharya, J. (2008). Deconstructing insight: EEG correlates of insightful problem solving. *PLoS ONE*, *3*, e1459.

Shu-Chen, L., & Sverker, S. (2002). Integrative neurocomputational perspectives on cognitive aging, neuromodulation, and representation. *Neuroscience & Biobehavioral Reviews*, *262*, 795–808.

Sigala, N. (2004). Visual categorization and the inferior temporal cortex. *Behavioural Brain Research*, *149*, 1–7.

Sigala, N., & Logothetis, N. K. (2002). Visual categorization shapes feature selectivity in the primate temporal cortex. *Nature*, *415*, 318–320.

Sloutsky, V. M., Kloos, H., & Fisher, A. V. (2007). When looks are everything: Appearance similarity versus kind information in early induction. *Psychological Science*, *18*(2), 179–185.

Smith, E. M., Ford, J. K., & Kozlowski, S. W. J. (1997). Building adaptive expertise: Implications for training design strategies. In M. A. Quinones & A. Ehrenstein (Eds.), *Training for a rapidly changing workplace* (pp. 89–118). Washington, DC: American Psychological Association.

Speed, A. (2008). Computational modeling of analogy: Destined ever to only be metaphor? *Behavioral and Brain Sciences*, *31*(3), 397–398.

Speed, A., Verzi, S., Benz, Z., Dixon, K. R., & Warrender, C. (in preparation). A computational model of analogy making linking primary sensory to prefrontal cortex.

Spellman, B. A., & Holyoak, K. J. (1996). Pragmatics in analogical mapping. *Cognitive Psychology*, *31*, 307–346.

Spellman, B. A., Holyoak, K. J., & Morrison, R. G. (2001). Analogical priming via semantic relations. *Memory and Cognition*, *29*(3), 383–393.

Squire, L. R. (1994). Declarative and nondeclarative memory: Multiple brain systems supporting learning and memory. In D. L. Schacter & E. Tulving (Eds.), *Memory systems* (pp. 203–231). Cambridge, MA: MIT Press.

Stuss, D. T. (2007). New approaches to prefrontal lobe testing. In B. L. Miller & J. L. Cummings (Eds.), *The human frontal lobes: Functions and disorders* (2nd ed., pp.292–305). New York: Guilford.

Sylvester, C. Y., & Shimamura, A. P. (2002). Evidence for intact semantic representations in patients with frontal lobe lesions. *Neuropsychology*, *16*(2), 197–207.

Tamura, H., & Tanaka, K. (2001). Visual response properties of cells in the ventral and dorsal parts of the macaque inferotemporal cortex. *Cerebral Cortex*, *11*, 384–399.

Thompson-Schill, S. L., Ramscar, M., & Chrysikou, E. G. (2009). Cognition without control: When a little frontal lobe goes a long way. *Current Directions in Psychological Science*, *18*, 259–263.

Unterrainer, J. M., Owen, A. M. (2006). Planning and problem solving: From neuropsychology to functional neuroimaging. *Journal of Physiology – Paris*, *99*(4–6), 308–317.

Vicario, C. M., Pecoraro, P., Turriziani, P., Kock, G., Caltagirone, C., & Oliveri, M. (2008). Relativistic compression and extension of experiential time in the left and right space. *PLoS ONE*, *5*(3), e1716.

Viskontas, I., Morrison, R. G., Holyoak, K. J., Hummel, J. E., & Knowlton, B. J. (2004). Relational integration, inhibition and analogical reasoning in older adults. *Psychology and Aging*, *19*, 581–591.

Wallis, J. D., Anderson, K. C., & Miller, E. K. (2001). Single neurons in prefrontal cortex encode abstract rules. *Nature*, *411*, 953–956.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*, 483–488.

Waltz, J. A., Knowlton, B. J., Holyoak, K. J., Boone, K. B., Mishkin, F. S., de Menezes Santos, M., et al. (1999). A system for relational reasoning in human prefrontal cortex. *Psychological Science*, *10*(2), 119–125.

Wartenburger, I., Heekeren, H. R., Preusse, F., Kramer, J., & van der Meer, E. (2009). Cerebral correlates of analogical processing and their modulation by training. *NeuroImage*, *48*, 291–302.

Wendelken, C., Nakhabenko, D., Donohue, S. E., Carter, C. S., & Bunge, S. A. (2007). “Brain is to thought as stomach is to ?”: Investigating the role of rostrolateral prefrontal cortex in relational reasoning. *Journal of Cognitive Neuroscience*, *20*(4), 682–693.

Wharton, C. M., Grafman, J., Flitman, S. S., Hansen, E. K., Bauner, J., Marks, A., et al. (2000). Toward neuroanatomical models of analogy: A positron emission tomography study of analogical mapping. *Cognitive Psychology*, *40*, 173–197.

Wood, J. N., & Grafman, J. (2003). Human prefrontal cortex: Processing and representational perspectives. *Nature Reviews Neuroscience*, *4*, 139–147.

Wright, S. B., Matlen, B. J., Baym, C. L., Ferrer, E., & Bunge, S. A. (2008). Neural correlates of fluid reasoning in children and adults. *Frontiers in Human Neuroscience*, *1*, 1–8.

Yeats, R. M., & Yeats, M. F. (2007). Business change process, creativity and the brain: A practitioner’s reflective account with suggestions for future research. *Annals of the New York Academy of Sciences*, *1118*, 109–121.

Downloaded By: [University of California, Los Angeles] At: 19:25 7 June 2010