Conclusion

The same dynamic process seems to underlie habituation, forgetting and interval timing, and it behaves like a cascade of thresholded integrators with progressively slower time constants. But many theoretical and experimental uncertainties remain. How exactly are the events that the organism uses as a time marker encoded? Tough questions have been raised about suggested applications of the MTS model to the choose-short effect, for example [14]. Exactly how best to generalize the memory-trace model to the learning of multiple time intervals has not been settled, nor are animals' limits in this regard well defined experimentally. Many other experimental questions remain. For an animal, as for a busy worker who might be late even if his watch is accurate, competing activities can affect timing: too much competition from other activities, and the target response might occur late; too little and it will be early [15]. Hence timing data can be affected by variables that act on activity levels rather than memory. And all the neurophysiological experiments necessary to cement the link between memory and timing have not yet been done. Do drugs or lesions that impair short-term memory (in delayed-match-to-sample tasks, for example) invariably impair timing of short intervals? Is the pattern of memory impairment matched by appropriate changes in temporal discrimination? Despite these uncertainties, the idea that the 'clock' that animals use in interval timing experiments is not a separate entity but a process based on memory strength looks like the best current view.

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References

- 1 Lewis, P.A. *et al.* (2003) Interval timing in mice does not rely upon the circadian pacemaker. *Neurosci. Lett.* 348, 131–134
- 2 Staddon, J.E.R. et al. (2002) Habituation, memory and the brain: the dynamics of interval timing. Behav. Processes 57, 71–88
- 3 Cerutti, D.T. and Staddon, J.E.R. (2004) Immediacy vs. anticipated delay in the time-left experiment: a test of the cognitive hypothesis. J. Exp. Psychol. Anim. Behav. Process. 30, 45–57
- 4 Staddon, J.E.R. (1965) Some properties of spaced responding in pigeons. J. Exp. Anal. Behav. 8, 19–27
- 5 Gibbon, J. (1977) Scalar expectancy and Weber's law in animal timing. Psychol. Rev. 84, 279–325
- 6 Staddon, J.E.R. and Innis, N.K. (1966) An effect analogous to 'frustration' on interval reinforcement schedules. *Psychonomic Sci* 4, 287–288
- 7 Sokolov, E.N. (1963) Higher nervous functions: the orienting reflex. Annu. Rev. Physiol. 25, 545–580
- 8 Staddon, J.E.R. and Higa, J.J. (1996) Multiple time scales in simple habituation. *Psychol. Rev.* 103, 720–733
- 9 Rubin, D.C. and Wenzel, A.E. (1996) One hundred years of forgetting: a quantitative description of retention. *Psychol. Rev.* 103, 736–760
- 10 Staddon, J.E.R. et al. (2001) Plus ça change...: Jost, Piaget and the dynamics of embodiment. Behav. Brain Sci. 24, 63–65
- 11 Uusitalo, M.A. *et al.* (1996) Dynamical organization of the human visual system revealed by lifetimes of activation traces. *Neurosci. Lett.* 213, 149–152
- 12 Schon, K. *et al.* (2004) Persistence of parahippocampal representation in the absence of stimulus input enhances long-term encoding: a functional magnetic resonance imaging study of subsequent memory after a delayed match-to-sample task. *J. Neurosci.* 24, 11088–11097
- 13 Staddon, J.E.R. and Higa, J.J. (1999) Time and memory: towards a pacemaker-free theory of interval timing. J. Exp. Anal. Behav. 71, 215–251
- 14 Zentall, T.R. (1999) Support for a theory of memory for event duration must distinguish between test-trial ambiguity and actual memory loss. J. Exp. Anal. Behav. 72, 467–472
- 15 Staddon, J.E.R. (2001) Adaptive Dynamics: The Theoretical Analysis of Behavior, MIT Press/Bradford Press

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The role of the inferior frontal junction area in cognitive control

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Cognitive control processes refer to our ability to coordinate thoughts and actions in accordance with internal goals. In the fronto-lateral cortex such processes have been primarily related to mid-dorsolateral prefrontal cortex (mid-DLPFC). However, recent brainimaging and meta-analytic studies suggest that a region located more posterior in the fronto-lateral cortex plays a pivotal role in cognitive control as well. This region has been termed the inferior frontal junction area and can be

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functionally and structurally distinguished from mid-DLPFC.

In our daily life we continually alternate between different cognitive and motor operations with seemingly minimal effort. Cognitive psychology has assumed that this flexibility involves cognitive control processes [1]. Although several prefrontal and parietal areas have been discussed as being involved in cognitive control, the literature most consistently pointed to mid-DLPFC as the crucial fronto-lateral area in cognitive control [2]. However, a recent series of brain imaging studies and

Box 1. Relation of the inferior frontal junction (IFJ) to existing cytoarchitectonic maps

The IFJ is located within a transition zone between premotor and prefrontal cortex. According to Brodmann [13], the IFJ primarily includes parts of Brodmann areas 6, 9, and 44. However, complicating the issue of assigning activations of the IFJ to existing cortical areas, the cortex on the posterior surface of the middle frontal gyrus has received different cytoarchitectonic labels by different researchers. For example, in Brodmann's map [13], cortex on the middle frontal gyrus adjacent to area 6 is labelled area 9. In the map of Petrides and Pandya [14], however, this cortex is labelled area 8. Consequently, imaging studies have labelled activations of the IFJ inconsistently as belonging to one or any combination of the abovementioned areas. In spite of this inconsistent labelling, however, it is clear that given its posterior location in the lateral frontal cortex, the IFJ is not part of the mid-DLPFC. This conclusion is further supported by recent structural neuroanatomical work, suggesting that the IFJ can be distinguished from adjacent areas on the basis of its cytoarchitectonic- and receptor features [15].

quantitative meta-analyses has revealed that a region in more posterior fronto-lateral cortex, which has been largely neglected so far, also seems to serve a crucial role in cognitive control [3–7]. Because of its anatomical location (see Box 1 and Figure 1) this region was termed the inferior frontal junction area (IFJ).

The role of the IFJ in task switching and set shifting

Brain imaging research is sometimes a self-fulfilling prophecy. When a specific brain area has been established to be related to a cognitive process, a multitude of brain imaging studies report activation in the same area. However, closer inspection often reveals either that activations assumed to be located in the area of interest are in fact located in other brain areas, or relevant activations which were not located in the crucial area are ignored. A good example of the latter case is the neglected role of IFJ in cognitive control.

Cognitive control refers to our ability to orchestrate our thoughts and actions in accordance with internal goals. In cognitive psychology this ability is frequently tested with so-called task switching or set shifting paradigms. In such experiments, participants are required to alternate between different tasks or cognitive operations. In comparison with repeating the same task, switching between two tasks leads to prolonged reaction times and higher error rates, the so-called switch costs. It has been argued that switch costs reflect cognitive processes needed to adjust to a new task, reflecting the prototypical cognitive control demand (see [8] for an overview).

Although the mid-DLPFC is commonly assumed to play a crucial role in task switching and set shifting, recent quantitative meta-analyses of task-switching and setshifting paradigms revealed the most consistent activation overlap in IFJ rather than mid-DLPFC [6]. Furthermore, a series of task-switching studies has revealed the specific functional role of IFJ in task switching [3,9]. These studies demonstrate that the IFJ is involved in the activation of task representations, a process that allows us to adjust our behaviour in advance to a new task environment. However, if the IFJ plays such a crucial role in cognitive control it should be activated not only In task-switching and set-shifting paradigms but also in other cognitive control paradigms.

IFJ involvement in other cognitive control tasks

One of the oldest and most widely used experimental paradigms to investigate cognitive control is the Stroop task [10]. The Stroop task requires a highly overlearned

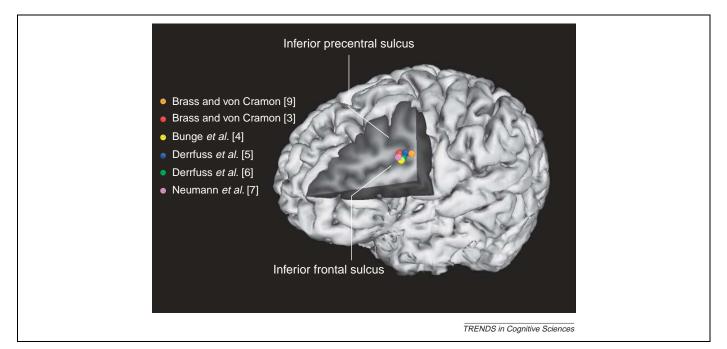


Figure 1. Lateral view of the human brain, showing the anatomical location of the inferior frontal junction (IFJ), at the junction of the inferior frontal sulcus and the inferior precentral sulcus. The peak activation foci of the studies discussed in this article are plotted in Talairach space. According to our functional data the location of the IFJ in Talairach space is x: +/-47, y: 1 to 10, z: between 27 and 40. Note that these coordinates provide only an approximate orientation of the IFJ's likely location rather than strict limits of its extension.

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response - reading - to be inhibited in favour of an unusual response - naming the colour of a word. Again it has been assumed that the fronto-lateral component involved in this task is located in mid-DLPFC. However, in a recent meta-analysis, Neumann and colleagues [7] compared 15 Stroop studies using a new meta-analytic algorithm. In the fronto-lateral cortex two areas showed a consistent activation: the IFJ and mid-DLPFC. Furthermore, Derrfuss and colleagues [6] carried out a meta-analysis on a largely different set of Stroop studies and also found IFJ involvement. A crucial aspect of the Stroop task is enforcing the non-dominant task (naming the colour of the word) against the dominant task (reading). In this sense, the Stroop task requires the activation of task representations. Finally, a within-subject comparison of three cognitive control tasks (a task-switching paradigm, a Stroop task and a n-back task) yielded an overlapping activation in the IFJ [5]. Given these findings, it appears that the primary role attributed to mid-DLPFC in the context of cognitive control and frontolateral cortex function is owed to the fact that consistent activation in the IFJ has been ignored.

The IFJ at the junction of three functional neuroanatomical domains

A plausible explanation for the IFJ's lack of recognition in the literature could be that the IFJ is located at the junction of three functional neuroanatomical domains, namely the premotor domain, the language domain and the working memory domain. Although we assume that the IFJ constitutes a functionally and structurally separable area in the fronto-lateral cortex, its functional role might well be to integrate information from these domains. Task representations can be understood as an abstraction of stimulus-response rules, which are processed in the premotor cortex [11]. Furthermore, it is reasonable to assume that verbalization of task goals plays a crucial role in task-related control processes [12]. This would be consistent with the finding that regions located very close to the IFJ are thought to be involved in phonological processing or silent articulation. Although we do not think that the role of the IFJ in cognitive control can be entirely accounted for by silent articulation, it is possible that the IFJ receives input from language-related areas. Finally, maintenance and manipulation of information in working memory is necessary to relate environmental information to internal goals and action plans. In this sense, the IFJ is strategically perfectly located to promote the interaction of information coming from these three domains to allow us to flexibly adjust our behaviour to a complex and changing environment.

Conclusions

Taken together, the findings discussed above provide strong evidence for the assumption that the IFJ constitutes a functionally separable area in the fronto-lateral cortex. Furthermore, this research suggests that the IFJ is involved in the activation of task representations. Future research has to show whether this functional description is general enough to account for the involvement of IFJ in other cognitive domains, like language and memory. Another open issue concerns the interaction of the IFJ with other cortical regions in the fronto-lateral and frontomedian cortex. On a more general level, these findings suggest that a careful functional parcellation of the prefrontal cortex can lead to new insights, on both neuroanatomical and functional levels.

References

- Monsell, S. (1996) Control of mental processes. In Mysteries of the Mind: Tutorial Essays on Cognition (Bruce, V., ed.), pp. 93–148, Erlbaum
- 2 Petrides, M. (2000) Mapping prefrontal cortex systems for the control of cognition. In *Brain Mapping: The Systems* (Toga, A.W. and Mazziotta, J.C., eds), pp. 159–176, Academic Press
- 3 Brass, M. and von Cramon, D.Y. (2004) Decomposing components of task preparation with functional magnetic resonance imaging. J. Cogn. Neurosci. 16, 609–620
- 4 Bunge, S.A. et al. (2003) Neural circuits subserving the retrieval and maintenance of abstract rules. J. Neurophysiol. 90, 3419–3428
- 5 Derrfuss, J. *et al.* (2004) Cognitive control in the posterior frontolateral cortex: evidence from common activations in task coordination, interference control, and working memory. *Neuroimage* 23, 604–612
- 6 Derrfuss, J. et al. (2005) Involvement of the inferior frontal junction in cognitive control: meta-analyses of switching and Stroop studies. *Hum. Brain Mapp.* 25, 22–34
- 7 Neumann, J. et al. (2005) The meta-analysis of functional imaging data using replicator dynamics. Hum. Brain Mapp. 25, 165–173
- 8 Monsell, S. (2003) Task switching. Trends Cogn. Sci. 7, 134-140
- 9 Brass, M. and von Cramon, D.Y. (2002) The role of the frontal cortex in task preparation. *Cereb. Cortex* 12, 908–914
- 10 MacLeod, C.M. (1991) Half a century of research on the Stroop effect: an integrative review. Psychol. Bull. 109, 163–203
- 11 Wise, S.P. (1985) The primate premotor cortex: past, present, and preparatory. Annu. Rev. Neurosci. 8, 1–19
- 12 Goschke, T. (2000) Intentional reconfiguration and voluntary persistence in task switching. In *Control of Cognitive Processes: Attention and Performance Vol. XVIII* (Monsell, S.C. and Driver, J., eds), pp. 331–355, Erlbaum
- 13 Brodmann, K. (1909) Vergleichende Lokalisationslehre der Groβ hirnrinde in ihren Prinzipien dargestellt auf Grund des Zellenbaues, Barth
- 14 Petrides, M. and Pandya, D.N. (1994) Comparative architectonic analysis of the human and the macaque frontal cortex. In *Handbook of Neuropsychology* (Vol. 9) (Boller, F. and Grafman, J., eds), pp. 17–58, Elsevier
- 15 Amunts, K. *et al.* (2004) A receptor- and cytoarchitectonic correlate of the functionally defined inferior-frontal junction area. *Neuroimage* 22 (Suppl.), 50

1364-6613/\$ - see front matter 0 2005 Elsevier Ltd. All rights reserved. doi:10.1016/j.tics.2005.05.001