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Review

Role of sensory modality and motor planning in the slowing of patients with traumatic brain injury: A meta-analysis

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ABSTRACT

Here we present a meta-analysis of studies that examined the reaction times (RT) of patients with traumatic brain injury (TBI) on decision tasks carried out under time pressure. To detect the presence of global components in the data describing the slowing of TBI patients, we used predictions of the difference engine model (DEM). According to this model, performance can be understood by referring to two separate and independent compartments, one cognitive and one sensory–motor.

Results confirm previous observations that TBI patients are delayed with respect to matched controls by a multiplicative factor affecting performance over and above the specific characteristics of the tasks. This meta-analysis also shows that the global factor affecting TBI patients' performance is selective for the visual modality. No over-additivity was detected on tasks in the acoustic modality. Estimates of the time taken by the sensory–motor component of the task indicated substantial slowing in the TBI patients. This delay was particularly marked in patients with severe TBI.

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1. Introduction

After traumatic brain injury (TBI), patients' reaction times (RT) are slowed on a large variety of decision tasks carried out under time pressure. Many authors share the view that this pattern indicates a pervasive deficit in speed of information processing (van Zomeren and Brouwer, 1994; Ferraro, 1996). According to van Zomeren and Brouwer (1994), the RT slowing is due to diffuse brain damage and affects all phases of processing. Consistently, Spikman et al. (1996) reported that deficits in focused and divided attention disappeared when slow information processing was controlled by co-variance analysis. Ferraro (1996) carried out a meta-analysis of relevant studies using the Brinley plot/regression analysis technique. In this approach, the mean performance of TBI patients on a variety of tasks is regressed on that of matched controls in the same conditions. Regression slopes greater than 1 indicate that as task difficulty increases patient groups are increasingly impaired. The linear regression accounted for a large proportion of variance and the slope of the regression indicated

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slowing of the TBI group by a factor of 1.54. Interestingly, this slowing is very similar to that reported for aging. For example, Myerson et al. (1992) found that older individuals were ca. 1.5 times slower then young adults. In fact, the effect of TBI has been viewed as an acceleration of normal aging (Ferraro, 1996; van Zomeren and Brouwer, 1994).

Several authors endorse the idea that traumatic brain injury has a very general and pervasive effect on performance; but other studies report more selective effects on specific stages of information processing. Using a paradigm based on Sternberg's (1969) additive factor method (AFM), Shum et al. (1990, 1994) found that patients with severe short-term injuries were impaired in the identification and response-selection stages of information processing (but not in the feature-extraction or motor-adjustment stages). Patients with severe long-term lesions were impaired only in the response-selection stage. By contrast, there was no evidence of impairment in any information-processing stage in patients with mild TBI. In these studies, the presence of selective deficits was inferred because TBI patients showed a disproportionate effect on variables hypothesized to act on single processing stages by generating group by stage manipulation interactions. One general problem in examining group by condition interactions (as in the studies that used the AFM) is that they may be affected by over-additivity, that is, the tendency of a generally slower group of individuals to show greater effects in the case of more difficult conditions over and above the specific effect of a given experimental condition (e.g., Faust et al., 1999). Indeed, this over-additivity tendency is captured by the regression, or Brinley, analysis. Bashore and Ridderinkhof (2002) replicated and extended the meta-analysis carried out by Ferraro (1996) and obtained very similar results (see left plot in their Fig. 4). They also carried out a complex, in-depth re-analysis of Shum et al.'s (1990, 1994) data in an attempt to tease out general versus specific components in the slowing of TBI patients.

The debate over general versus specific interpretations of RT slowing has focused on the type of cognitive processes involved and whether or not they belong to selective stages of processing, such as those envisaged in the AFM (Sternberg, 1969; Bashore and Ridderinkhof, 2002). Other more basic variables have received considerably less attention. For example, whether cognitive slowing varies as a function of the sensory modality in which stimuli are presented could be investigated. Clearly, the idea that slowing is general and concerns all processing stages suggests there is no difference among different modalities, for example, the visual versus acoustic modalities. At the same time, it seems unwarranted to assume that brain injuries affect responses similarly across tasks regardless of the stimulus modality. Indeed, cross-modal differences have been reported in ERP studies comparing TBI patients and matched controls (Doi et al., 2007; Werner and Vanderzant, 1991). Both of the previous meta-analyses (Ferraro, 1996; Bashore and Ridderinkhof, 2002) ignored this aspect and analyzed all studies together. It should be noted that in most studies stimuli were presented visually; therefore, it is not clear whether the slowing in information processing is in itself cross-modal or whether effects in the visual modality dominate the pattern of results so that they seem "general".

Another important question concerns the possible role of programming and execution components of the response in the generation of slowing in TBI patients. In general, gross motor deficits do not persist chronically after severe TBI (and if they do, they are easily diagnosed); thus, it is usually held that slowing of the response is cognitive in nature. However, it has been reported that motor integrative functions and fine motor skills are often deficient, co-vary with trauma severity and may persist several months after injury (e.g., Kuhtz-Buschbeck et al., 2003). Critically, they may have occult presentations and be rather difficult to detect (for a review, see McNamee et al., 2009). Notably, the assumption that the slowing of TBI patients is purely cognitive has been rarely tested. Indeed, when separate measures of execution times were examined, significant differences emerged between TBI patients and controls even if only patients with good motor recovery were included in the study.

In the studies by Shum et al. (1990, 1994), severe TBI patients showed impaired movement times as well as the RT deficit in selective cognitive stages. By contrast, patients with minor TBI (GCS scores of 14 or 15) produced movement times similar to controls and did not show selective deficits in RT measures. Incoccia et al. (2004) obtained similar results on severe patients using simple and choice reaction time tasks. Furthermore, Gray et al. (1998) reported evidence of subclinical bradykinesia in simple and complex RTs in chronic severe TBI patients. Thus, it seems that trauma severity co-varies with the presence of impaired motor and cognitive functions. Studies examining movement-related cortical potentials in TBI patients found selective differences between TBI patients and controls; the pathological group showed selective hypo-activation particularly in the supplementary motor area (Di Russo et al., 2005; Wiese et al., 2004). According to Di Russo et al. (2005), these results indicate that severe TBI patients have a deficit in motor preparation, but their pattern of activation during and following movement is relatively spared. Overall, deficits in motor programming and fine integrative functions may occur even in the absence of gross motor deficits and may be comparatively difficult to diagnose on the basis of standard clinical measures. Therefore, it seems important to distinguish between cognitive and motor components in the slowing of TBI patients.

In the present meta-analytic study, we built on previous analyses by Ferraro (1996) and Bashore and Ridderinkhof (2002) to clarify the RT slowing shown by TBI patients. In particular, we were interested in examining the role of the sensory modality used to present the target stimuli. The idea of general slowing predicts that the disturbance is cross-modal. However, as stated above, this prediction has not yet been tested. We also wished to examine whether sensory–motor components at least partially cause the slowing shown by TBI patients. A particularly useful model for investigating this is the difference engine model (DEM) proposed by Myerson et al. (2003).

The DEM makes explicit predictions about the presence and characteristics of global slowing in a given group of individuals. In particular, in the presence of global components describing the relation between a slow and a fast group, the DEM proposes that performance can be understood with reference to two separate and independent compartments, one cognitive and one sensory–motor. The cognitive (or central) compartment identifies the cognitive time that differentiates two groups of individuals with a global difference in processing efficiency across different tasks (e.g., young adults versus elderly). A different "sensory–motor" compartment identifies the amount of time required for peripheral analysis (sensory perception) and programming/beginning the motor response. This portion of the response is expected to be unrelated to the cognitive compartment.

As to predictions, the DEM incorporates the idea (already present in the previous analyses by Ferraro, 1996, and Bashore and Ridderinkhof, 2002) that plotting the condition means of the slow group against those of a control group yields a linear regression whose slope (beta) greater than 1 provides an estimate of the degree of slowing. Apart from these Brinley plots, linearity is also expected in plots contrasting standard deviations with means in the same conditions. Unlike what is typically assumed in ANOVA designs, this relationship indicates that the variance is not homogeneous across conditions and/or groups and that individual differences grow as task difficulty increases. Differences in RTs across conditions reveal distinct but correlated cognitive steps. More specifically, the DEM simulation of the linear