Staying on the job: the frontal lobes control individual performance variability

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Summary
The causes of variability of performance by individual subjects have rarely been investigated, although excessive variability or inconsistency may be a functionally significant factor for many real-life activities. Our objective was to determine whether patients with focal frontal brain lesions have excessive individual performance variability. Thirty-six patients with focal frontal (n = 25) or non-frontal (n = 11) lesions were compared with 12 control subjects on different measures of intra-individual variability: dispersion within a testing session; and consistency across testing sessions. Four reaction time tasks, varying in levels of complexity and based on a model of detection using feature integration, were administered. Following the first test session, 22 patients and 10 controls returned for two subsequent test sessions, which permitted the assessment of consistency of performance. Measures of abnormal dispersion of performance on these tests were observed in frontal patients only (except those with exclusively inferior medial damage). Disturbances in consistency of performance were observed primarily in patients with frontal lesions. Damage to the frontal lobes impairs the stability of cognitive performance. Damage to different frontal regions causes different profiles of abnormal variability. Fluctuations in performance of a task may underlie some of the reported difficulties in daily tasks reported by patients with frontal injuries.

Keywords: frontal lobes; reaction time; individual differences; intra-individual variability; attention

Abbreviations: CTL = control; DL = dorsolateral; ICV = intra-individual coefficient of variation; IIV = intra-individual variability; IM = inferior medial; ISD = intra-individual standard deviation; LDL = left dorsolateral; NF = non-frontal; RDL = right dorsolateral; RT = reaction time; SM = superior medial; TBI = traumatic brain injury; TSI = time since injury.

Introduction
Analysis of quantitative neuropsychological tests requires consideration of performance variability on the tests. There are different types of variability and they have different consequences for analysis of different methods of control. Diversity is the variation of performance between subjects in a group; it is inter-individual variability and is usually viewed as ‘noise’. Diversity is sometimes successfully controlled by methodological techniques: using a consistent test environment; creating homogeneous groups; the extreme example being single subject studies; or using very large groups (Cronbach, 1957).

Variation of performance of an individual subject may also contribute ‘noise’. It may also be a source of considerable information (Flugel, 1928; Philpott, 1933; Fiske and Rice, 1955; Cronbach, 1957; Barratt, 1963) and there is a substantial history of studying intra-individual variability (IIV) as the dependent measure of interest (Stuss et al., 1989). IIV is short-term fluctuation in performance, not the durable and systematic change due to practice, learning, developmental growth, trait alterations or, in clinical practice, improvement or progression of the medical problem. There are two general types of IIV. Dispersion is the oscillation of performance by
Factors affecting variability of performance

It is difficult to generate detailed predictions about the causes of IIV from prior studies because of differences in working definitions of variability, task demands, statistical methods and subject populations—some normal and others clinical. There are, however, some factors that have been identified as possible contributors to IIV. Increased age is frequently cited as a cause of greater variability of performance and of inconsistency (Fozard et al., 1994; Shammi et al., 1998; Anstey, 1999), but this aging effect is task or measurement dependent (Foster et al., 1995; Lindenberger and Baltes, 1997; Shammi et al., 1998). Normal aging (Salthouse, 1993, 1996; Fozard et al., 1994) and many neurological disorders (van Zomeren and Brouwer, 1994; Whyte et al., 1995; Collins and Long, 1996; Bleiberg et al., 1998; Leth-Steensen et al., 2000) produce a general slowing on numerous reaction time (RT) tasks, and overall RT slowing may be accompanied by variability of RT. The association is not sufficient to account for all variability in RT performance. In some experiments, no association has been found between overall RT and IIV (Benton and Blackburn, 1957; Bruhn and Parsons, 1971; Schwartz et al., 1989; Hetherington et al., 1996). In other reports, the correlation between overall RT and IIV has been quite inconsistent depending on the exact variability measure (Shammi et al., 1998).

Tasks that appear to require more active control of attention are often labelled ‘complex’, although complexity can surely be generated along many task dimensions. Perhaps because of differences in working definition, complexity has had a mixed effect on performance variability. In some studies, task complexity increased IIV (Stuss et al., 1994b; Shammi et al., 1998; West et al., 2002b) but, in others, it did not (Bruhn and Parsons, 1971; Zahn et al., 1991; Foster et al., 1995).

Whether the mechanism of increased IIV is due to some aspect of complexity or to slower overall responses or to some other fundamental psychophysiological process, it has been observed for many years that brain damage causes increased IIV (Head, 1926; Goldstein, 1942; Benton and Blackburn, 1957). This variability may be of two general types. There may be increased IIV that is specific to a discrete cognitive process, and probably always associated with impairment to that process. Thus, patients with right brain damage and spatial neglect show increased variability on bisection tasks (Anderson et al., 2000) and patients with left brain damage and aphasia appear to show increased IIV on lexical decision tasks (Milberg et al., 2003). There may also be increased IIV due to a general deficit in regulation of attention to any task. The general deficit would not be associated with any distinct cognitive domain, and this form of increased IIV has been most consistently described in patients with ‘executive’ impairments, with or without overt demonstration of focal frontal lesions.

Trauma

Since the initial report of Goldstein (Goldstein, 1942) demonstrating increased IIV (and overall slow RT), numerous studies have confirmed increased dispersion or reduced consistency in patients with traumatic brain injury (TBI) at all levels of severity, with or without focal frontal lesions (Stuss et al., 1989, 1994b; Whyte et al., 1995; Collins and Long, 1996; Hetherington et al., 1996; Spikman et al., 1996; Segalowitz et al., 1997; Bleiberg et al., 1997, 1998; Zahn and Mirsky, 1999).

Dementia

Patients with a variety of dementing illnesses are also reported to be more variable in performance than normal elderly (Hultsch et al., 2000). There is an apparent ordering of the level of variability in different dementing disorders. Patients with Lewy body disease exhibit the greatest fluctuation of performance, followed by vascular dementia and then Alzheimer’s disease (Walker et al., 2000; Ballard et al., 2001). Murtha et al. (2002) showed that patients with frontal–temporal dementia have more IIV than those with Alzheimer’s disease.

Miscellaneous

Increased IIV has also been reported in schizophrenia (but not affective disorders) (Schwartz et al., 1989), and in attention deficit disorder and conduct disorder (Zahn et al., 1991; Leth-Steensen et al., 2000).

In both normal subjects and clinical groups, IIV is sensitive to ‘executive control’. In normal subjects, IIV is sensitive to the demand for executive control (Shammi et al., 1998; West, 1999a). In normals, West et al., (2002b) concluded that increased IIV was limited ‘almost exclusively’ to task conditions requiring the active demands of such executive control processes. In TBI, IIV is closely associated with impaired maintenance of consistent ‘top-down’ attentional processes (Stuss et al., 1989, 1994b; Stuss, 1991). The hierarchy of IIV in dementias parallels the relative frontal system damage; individuals with Alzheimer’s disease have the least involvement of the frontal lobes and the least IIV.

There have been no direct experiments to determine whether lesions in any focal region of the frontal lobes are critical in the production of increased IIV, but there is indirect evidence that suggests that right dorsolateral (RDL) lesions may be particularly likely to increase IIV. Right frontal lesions impair top-down attentional control (Fink et al., 1997). Patients with right frontal lesions make excessive errors due to a lowered inhibition to distracting information
To assess the effects of focal lesions on IIV, we used RT tasks designed to allow serial analyses of reaction times and errors moving from simple RT to increasingly more complex RT tasks, including the ability to analyse the effect of redundant information. Four different types of RT tasks were administered (Stuss et al., 2002b). The theoretical framework for task design was detection using feature integration. Complexity was defined by the type and number of features that had to be analysed. The higher level of task included the mental operations of the previous task, plus an added process (Donders, 1969; Sternberg, 1969). This task was selected

Table 1 Aetiology, lesion location, lesion size*, time since injury and handedness within patient groups

<table>
<thead>
<tr>
<th>Subject</th>
<th>Aetiology</th>
<th>Lesion location</th>
<th>Lesion size (%)</th>
<th>TSI (months)</th>
<th>Handedness</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDL frontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1019</td>
<td>Trauma</td>
<td>DL, ACG, IM, polar</td>
<td>0.87</td>
<td>31.1</td>
<td>Right</td>
</tr>
<tr>
<td>1021</td>
<td>Stroke</td>
<td>DL</td>
<td>1.03</td>
<td>2.8</td>
<td>Right</td>
</tr>
<tr>
<td>1027</td>
<td>Stroke</td>
<td>DL, polar, medial</td>
<td>3.76</td>
<td>18.3</td>
<td>Right</td>
</tr>
<tr>
<td>1029</td>
<td>Stroke</td>
<td>DL</td>
<td>1.76</td>
<td>24.0</td>
<td>Left</td>
</tr>
<tr>
<td>1053</td>
<td>Trauma</td>
<td>DL</td>
<td>0.92</td>
<td>291.1</td>
<td>Right</td>
</tr>
<tr>
<td>2012</td>
<td>Tumour</td>
<td>DL, SM, ACG</td>
<td>1.46</td>
<td>3.8</td>
<td>Right</td>
</tr>
<tr>
<td>RDL frontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1017</td>
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<td>3.04</td>
<td>1.3</td>
<td>Left</td>
</tr>
<tr>
<td>1041</td>
<td>Lobectomy</td>
<td>DL, IM</td>
<td>2.92</td>
<td>4.2</td>
<td>Right</td>
</tr>
<tr>
<td>1054</td>
<td>Tumour</td>
<td>IM, DL, ACG</td>
<td>2.55</td>
<td>24.7</td>
<td>Right</td>
</tr>
<tr>
<td>1055</td>
<td>Stroke</td>
<td>SM, DL</td>
<td>5.09</td>
<td>10.9</td>
<td>Right</td>
</tr>
<tr>
<td>1067</td>
<td>Stroke</td>
<td>DL</td>
<td>0.84</td>
<td>21.0</td>
<td>Right</td>
</tr>
<tr>
<td>2001</td>
<td>Stroke</td>
<td>DL, striatal</td>
<td>3.26</td>
<td>5.3</td>
<td>Right</td>
</tr>
<tr>
<td>2024</td>
<td>Stroke</td>
<td>DL, striatal</td>
<td>1.74</td>
<td>2.5</td>
<td>Right</td>
</tr>
<tr>
<td>IM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1023</td>
<td>Stroke</td>
<td>Striatal, caudate, IM(L), ACG(L)</td>
<td>0.85</td>
<td>26.7</td>
<td>Both</td>
</tr>
<tr>
<td>1056</td>
<td>Stroke</td>
<td>IM, ACG</td>
<td>1.60</td>
<td>33.1</td>
<td>Both</td>
</tr>
<tr>
<td>1059</td>
<td>Trauma</td>
<td>IM, DL, ACG</td>
<td>4.47</td>
<td>34.1</td>
<td>Left</td>
</tr>
<tr>
<td>1065</td>
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<td>IM</td>
<td>1.30</td>
<td>15.6</td>
<td>Right</td>
</tr>
<tr>
<td>1069</td>
<td>Tumour</td>
<td>IM</td>
<td>0.22</td>
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<td>Right</td>
</tr>
<tr>
<td>2013</td>
<td>Stroke</td>
<td>IM, septal, ACG</td>
<td>0.07</td>
<td>8.9</td>
<td>Right</td>
</tr>
<tr>
<td>SM (+ IM)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1011</td>
<td>Trauma</td>
<td>Medial, DL(L), ACG</td>
<td>7.17</td>
<td>13.9</td>
<td>Right</td>
</tr>
<tr>
<td>1044</td>
<td>Stroke</td>
<td>IM, polar, ACG, SM(L)</td>
<td>3.20</td>
<td>118.9</td>
<td>Right</td>
</tr>
<tr>
<td>2002</td>
<td>Stroke</td>
<td>Medial, DL, ACG(L)</td>
<td>1.19</td>
<td>4.6</td>
<td>Right</td>
</tr>
<tr>
<td>2011</td>
<td>Stroke</td>
<td>SM, ACG</td>
<td>1.60</td>
<td>3.6</td>
<td>Right</td>
</tr>
<tr>
<td>2045</td>
<td>Stroke</td>
<td>Medial, septal, ACG</td>
<td>7.43</td>
<td>59.8</td>
<td>Right</td>
</tr>
<tr>
<td>2167</td>
<td>Tumour</td>
<td>Medial, polar</td>
<td>5.46</td>
<td>6.0</td>
<td>Right</td>
</tr>
<tr>
<td>NF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1049</td>
<td>Tumour</td>
<td>Temporal (Left)</td>
<td>NA</td>
<td>17.8</td>
<td>Right</td>
</tr>
<tr>
<td>1058</td>
<td>Stroke</td>
<td>Parietal (Left)</td>
<td>NA</td>
<td>3.5</td>
<td>Right</td>
</tr>
<tr>
<td>2028</td>
<td>Stroke</td>
<td>Temporal, occipital (Left)</td>
<td>0.95</td>
<td>28.5</td>
<td>Right</td>
</tr>
<tr>
<td>2032</td>
<td>Lobectomy</td>
<td>Temporal (Left)</td>
<td>1.60</td>
<td>49.6</td>
<td>Right</td>
</tr>
<tr>
<td>2036</td>
<td>Lobectomy</td>
<td>Temporal (Left)</td>
<td>NA</td>
<td>91.3</td>
<td>Right</td>
</tr>
<tr>
<td>2038</td>
<td>Lobectomy</td>
<td>Temporal (Left)</td>
<td>1.17</td>
<td>144.7</td>
<td>Right</td>
</tr>
<tr>
<td>2040</td>
<td>Lobectomy</td>
<td>Temporal (Right)</td>
<td>2.06</td>
<td>89.3</td>
<td>Right</td>
</tr>
<tr>
<td>2043</td>
<td>Stroke</td>
<td>Occipital (Right)</td>
<td>0.48</td>
<td>36.3</td>
<td>Right</td>
</tr>
<tr>
<td>2054</td>
<td>Lobectomy</td>
<td>Temporal (Left)</td>
<td>NA</td>
<td>142.6</td>
<td>Right</td>
</tr>
<tr>
<td>2057</td>
<td>Lobectomy</td>
<td>Temporal (Right)</td>
<td>2.66</td>
<td>134.6</td>
<td>Right</td>
</tr>
<tr>
<td>2103</td>
<td>Stroke</td>
<td>Parietal, occipital (Right)</td>
<td>0.74</td>
<td>34.6</td>
<td>Right</td>
</tr>
</tbody>
</table>

*Percentage lesion size of total brain volume for certain patients varied across studies by a minimal amount due to refinements in measurement. The variations do not alter any group differences. **See caption for Fig. 1. ACG = anterior cingulate gyrus; NA = not available.
because it had been used effectively to study RT and variability in traumatic brain-injured individuals (Stuss et al., 1989, 1994b). In each task, the subject had to detect a target stimulus and press a hand-held response button with the dominant hand as quickly as possible, making as few errors as possible. In some of the tasks, a non-target stimulus was presented, requiring a response using a second response button mechanism held in the non-dominant hand.

Fig. 1 Schematics of lesion location. The lesion location for the available scans for each patient in each of the defined patient groups is illustrated. In some cases, lesion location had been documented and the scan subsequently lost. As described in the text, the SM group is labelled superior medial, even though several of the group had extension into IM regions, to distinguish them from the group with IM lesions only.
There were several hypotheses derived from the previous literature:

(i) Patients with frontal lesions will show greater dispersion and inconsistency relative to control (CTL) group of participants and to patients with non-frontal (NF) lesions.

(ii) Based on previously demonstrated impairments in maintenance of sustained attention, patients with lesions of the right frontal lobe will have impaired consistency of performance; there is insufficient information in the literature to predict specific effects of other frontal lesion sites.

(iii) More complex RT tasks require more executive control and, thus, in patients with lesions of the frontal lobes, such tasks will elicit greater IIV than simpler RT tasks.

(iv) We presume that the effects of errors on dispersion will differ in the groups, but unique effects of different frontal lesions are not specifiable.

Methods

Subjects

Thirty-six patients with focal lesions documented by CT or MRI evidence were assessed. Inclusion criteria were as follows:

(i) The aetiology was an acquired acute disorder such as infarction, haemorrhage, trauma or resection of a benign tumour;

(ii) There had been sufficient time post-onset to allow for stability of the medical condition (range 1.3–291 months post-onset, mean = 42.4; all but one past 2.5 months);

(iii) Absence of severe aphasia or clinically detectable neglect;

(iv) There was a CT or MRI scan demonstrating unequivocal frontal or NF damage.

The exclusion criteria for patient subject selection were the following: untreated hydrocephalus on CT or MRI scan; presence of any systemic illness; history of alcoholism, hospitalization for a psychiatric disorder, or prior neurological illness. The varied aetiologies allowed for the assessment of potential localization differences within the frontal lobes (Stuss et al., 1995). In addition, the localization of the lesion has been reported as more relevant than the aetiology (Elsass and Hartelius, 1985; Stuss et al., 1994a; Burgess and Shallice, 1996).

The patients were divided into five groups based on the location of their primary lesion. Eleven patients had pathology located in NF regions (seven left, four right). They were combined into one group for two reasons: posterior hemispheric differences were not a focus of this study; and preliminary analyses indicated no consistent differences on the tasks used between the left and right posterior lesioned patients. The 25 patients with focal frontal lesions were divided into four groups based on the location of their primary lesions: (i) left dorsolateral (LDL) frontal (n = 6); (ii) right dorsolateral (RDL) frontal (n = 7); (iii) inferior medial (IM) (n = 6); and superior medial (SM) (n = 6). This classification derived from a history of 10 years of uncovering increasing anatomical/behavioural specificity within the frontal lobes (for reviews see Stuss et al., 2002a; Stuss and Levine, 2002). The patients classified as SM tended to have both IM and SM pathology. They were designated as SM to differentiate them from the patients who had IM pathology only. The five patient groups were compared with 12 control

<table>
<thead>
<tr>
<th>Sample size</th>
<th>Age (years)</th>
<th>Sex (proportion female)</th>
<th>Education (years)</th>
<th>National adult reading test</th>
<th>Digit span forward</th>
<th>Boston naming test</th>
<th>Beck depression inventory</th>
<th>Lesion size</th>
<th>Time since injury (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDL 6</td>
<td>53</td>
<td>0.67</td>
<td>12</td>
<td>100</td>
<td>4.5</td>
<td>37</td>
<td>4.7</td>
<td>1.6</td>
<td>62</td>
</tr>
<tr>
<td>RDL 7</td>
<td>57</td>
<td>0.29</td>
<td>10</td>
<td>102</td>
<td>5.3</td>
<td>52</td>
<td>1.2</td>
<td>2.8</td>
<td>10</td>
</tr>
<tr>
<td>SM 6</td>
<td>58</td>
<td>0.33</td>
<td>12</td>
<td>99</td>
<td>6.4</td>
<td>46</td>
<td>6.3</td>
<td>4.3</td>
<td>34</td>
</tr>
<tr>
<td>IM 6</td>
<td>46</td>
<td>0.17</td>
<td>11</td>
<td>100</td>
<td>6.0</td>
<td>47</td>
<td>4.2</td>
<td>1.4</td>
<td>20</td>
</tr>
<tr>
<td>NF 11</td>
<td>43</td>
<td>0.73</td>
<td>13</td>
<td>106</td>
<td>6.2</td>
<td>48</td>
<td>3.2</td>
<td>1.4</td>
<td>70</td>
</tr>
<tr>
<td>CTL 12</td>
<td>67</td>
<td>0.67</td>
<td>12</td>
<td>108</td>
<td>7.2</td>
<td>52</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>DL 6</td>
<td>61</td>
<td>0.40</td>
<td>10</td>
<td>101</td>
<td>5.3</td>
<td>48</td>
<td>3.8</td>
<td>2.2</td>
<td>56</td>
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<tr>
<td>SM 3</td>
<td>55</td>
<td>0.33</td>
<td>11</td>
<td>91</td>
<td>6.0</td>
<td>48</td>
<td>4.0</td>
<td>3.3</td>
<td>7.4</td>
</tr>
<tr>
<td>IM 4</td>
<td>55</td>
<td>0.25</td>
<td>9.3</td>
<td>99</td>
<td>6.3</td>
<td>50</td>
<td>3.5</td>
<td>1.6</td>
<td>20</td>
</tr>
<tr>
<td>NF 9</td>
<td>44</td>
<td>0.78</td>
<td>13</td>
<td>105</td>
<td>6.2</td>
<td>47</td>
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<td>1.3</td>
<td>74</td>
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<tr>
<td>CTL 10</td>
<td>66</td>
<td>0.70</td>
<td>12</td>
<td>108</td>
<td>7.2</td>
<td>52</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Groups with frontal lesions are LDL, RDL, SM, IM and combined DL. Brackets indicate sample size where missing values occur. As noted in the text, analyses were completed for the first day of assessment (ONE), and for three separate test sessions approximately one week apart (THREE). Because of attrition over the 3 weeks of testing, the patients with right or left lateral lesions were combined into one group labelled DL. The sample sizes for the various groups are given in the first column of the table. Size of lesion and TSI are summarized from Table 1 to allow comparison of the groups in the single assessment and three repeated assessments. There are missing values for some clinical variables. The size represents the percentage of lesion in relation to the total brain volume. TSI indicates the chronicity of the lesion when the patient was entered into the study. NA = not applicable.
subjects. The subjects were primarily right-handed. The presence of left-handed individuals were allowed in the different patient groups for the following reasons: (i) the left hander in the left brain damaged group was aphasic; (ii) the left hander in the right brain damaged group was not aphasic and had a typical right hemisphere syndrome; and (iii) the third left hander was in the IM non-impaired group, where laterality is not relevant. The lesion aetiology, location, lesion size, time since injury (TSI) (chronicity of lesion) and subject handedness are presented in Table 1. The individual lesions divided by group are illustrated in Fig. 1.

The National Adult Reading Test, Digit Span forward, Boston Naming Test, and Beck Depression Inventory were administered to all participants with a few exceptions. All subjects had normal colour vision. Demographic and clinical data are summarized for each of the groups in Table 2. The project was approved by the University of Toronto/Baycrest Centre Human Subjects’ Research Ethics Committee and consent for participation in the project was obtained for each participant according to the Declaration of Helsinki.

### Tasks and procedures

Stimuli measuring ~3 cm high and 3 cm wide were presented centrally on a 35 × 35 cm square colour monitor, located ~1 m from the subject’s head position, at a variable inter-stimulus interval lasting 4–6 s. Stimuli remained on the screen until a response was made or for a default duration of 2 s. Subjects responded to a designated target stimulus by pressing the button on a hand-held response mechanism with their dominant hand. Non-target stimuli, when presented, required a non-dominant hand response. Stimuli were always one of four shapes (circle, square, triangle or cross). Subjects were instructed to respond as quickly and as accurately as possible.

There were four different RT tasks requiring different levels of feature discrimination and identification; for more detailed explanations of the procedures, see Stuss et al. 1994b, 2002b).

(i) Simple RT (50 trials). A single shape, in light grey against the dark grey background of the computer screen, was presented;

(ii) Easy Choice RT (100 trials). Four different shapes were presented—one designated as target (25% chance occurrence) and the other three as non-targets (75%).

(iii) Complex RT (100 trials). The discrimination was based on three characteristics of the stimuli—shape, colour, and internal texture. The shapes appeared in one of four colours (yellow, green, blue and red) and contained internal texture in the form of lines that were oriented horizontally, oriented vertically, slanting forward or slanting backward. The target, representing ~25% of the trials, was defined as a particular combination of the three features (e.g. a red circle with horizontal lines). The non-targets could be any other combination of features.

(iv) Redundant RT (100 trials). In this task, the target was characterized by a combination of three separate features, but subjects were informed about the fact that none of the non-targets would contain any of the features in the target. That is, if the target were a yellow square with backward slanting lines, no other stimulus would be square, be coloured yellow, or have backward slanting lines. The Simple task was repeated after the Redundant task, but is not analysed here.

These tasks were presented in a fixed order.

### Measures of IIV/analyses of factors

Mean RT and errors for the first assessment have been presented elsewhere (Stuss et al., 2002b); the means and SDs for the RT results of this study are presented in Table 3 as background information. In this paper, the focus is on variation within an individual. There were two potential categories of IIV studied—dispersion and consistency of performance.

#### Measures of dispersion

Dispersion refers to IIV within the continuous time period of a single test. In our study, this was evaluated in the first test session. Each of the following scores was calculated for each individual for each of the five RT tasks.

**Intra-individual standard deviation (ISD)**

Within a task, we calculated the SD of each subject’s RTs for correct target trials. The ISD provided a general index of each subject’s performance spread about his or her mean RT.

**Intra-individual coefficient of variation (ICV)**

To investigate the possibility that longer RTs could also be more variable for the sole reason that they are farther away from the floor, we calculated coefficients of variation (ISD/mean) for each subject. The ICV measures performance controlled to some degree for speed of response. To validate the use of the ICV, we also investigated the relationship between speed and variability within each group using a linear model of subject’s SD in the Complex task as a

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<th>Table 3</th>
<th>Means and SDs of average reaction times</th>
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function of average RT, group membership, and the interaction between RT and group.

**Autocorrelation**
For each subject’s five tests, correlation between consecutive observations was calculated. This measure denoted how much linear association there was between one trial and the next.

**Factors possibly affecting dispersion**

**Task complexity**
The effect of task complexity, as defined in these feature integration tasks, on dispersion was analysed by comparing the effect of increasing complexity of choice offered by the Simple, Easy and Complex RT tasks.

**Speed of RT**
Since speed of RT has been related to increased variability (Salthouse, 1993), we examined the relation of average RT to ISD.

**Trends**
Steadily changing RT would increase IIV. To see if there was any linear drift in an individual’s RT across the duration of a task, we calculated the linear slope estimate for each subject’s five tests.

**Errors**
The presence of errors could be related to increased dispersion. We first determined whether there was a general relationship between the number of errors and IIV. We then examined the effect of errors on RT by calculating the following:

(i) The pre-error effect on RT, measured as the difference between RT for the trial immediately preceding an error and RT for the erroneous trial and calculated the average of these differences for each subject;

(ii) The post-error effect on RT, measured as the difference between the RT for an erroneous trial and the RT for the subsequent trial and averaged these differences for each subject.

**Consistency**
Consistency of performance is defined as the ability of an individual to perform comparably across different testing sessions. Inconsistency indicates impairment in this ability. In this study, to assess IIV across non-continuous time periods, the same tests were repeated on two additional occasions—all three testing sessions occurring ~1 week apart. For each test, the performance across the three sessions was compared for the following measures: mean RTs; number of errors; ISD; ICV; autocorrelations; effects of errors; and trends.

**Results**

**Demographic data**
In patient studies where the emphasis is on lesion localization, a variety of different abilities may occur in the different patient subgroups for which it is difficult to find controls. Our major focus in selecting the CTL group was to control for education and intelligence. There were no significant differences between any of the patient groups and the CTL group in this regard. Other significant demographic differences were observed. The age of the CTL group was significantly older than the NF group [F(1,42) = 23, \( P < 0.0001 \)], the IM group [F(1,42) = 13, \( P = 0.001 \)] and the LDL group [F(1,42) = 5.2, \( P = 0.03 \)]. Forward digit span was significantly shorter in the RDL [F(1,33) = 8.4, \( P = 0.007 \)] and LDL [F(1,33) = 7.7, \( P = 0.009 \)] groups relative to the CTL group. There were no differences among the patient groups on the Beck Depression Inventory measure—the group means ranging from 1.2 to 6.3, with no subject over 11. Among the patient groups, there was a significant difference in lesion size between the groups [F(4,27) = 3.8, \( P = 0.01 \)], with the SM group having the largest lesions.

For the comparison across the 3 days of testing, there remained six dorsolateral frontal (DL) patients (two LDL, four RDL), four IM patients, three SM patients, nine NF patients and 10 CTL participants. The DL group had a significantly shorter forward digit span [F(1,26) = 7.4, \( P = 0.01 \)] and the SM group had a significantly lower National Adult Reading Test score [F(1,25) = 8.7, \( P = 0.007 \)].

Demographic and neuropsychological variables showed similar statistical differences for the IM and NF groups on this reduced sample as in the full sample—except that the IM group was no longer different on age [F(1,27) = 2.4, \( P = 0.13 \)]. On this reduced sample, we found no effect of group on either lesion size or time since injury. Table 2 summarizes the demographic, neuropsychological and clinical characteristics for the sample of subjects who participated in the three test sessions.

**Dispersion: first test session**

**ISD**
ISD was calculated for each subject within each of the four tasks (Simple, Easy, Complex and Redundant) and group differences were investigated using simple contrasts between each lesion group and the CTL group. As presented graphically in Fig. 2, ISD was significantly higher on the Easy task for the SM [F(1,42) = 10, \( P = 0.003 \)], RDL [F(1,42) = 7.4, \( P = 0.009 \)] and LDL [F(1,42) = 7.1, \( P = 0.01 \)] groups relative to the CTL. ISD was significantly higher on the Complex task for the RDL [F(1,42) = 16, \( P = 0.0002 \), SM
[F(1,42) = 12, P = 0.001], LDL [F(1,42) = 5.9, P = 0.02] and NF [F(1,42) = 6.1, P = 0.02] groups relative to the CTL. ISD was significantly higher on the Redundant task for the SM [F(1,42) = 15, P = 0.0004] and LDL [F(1,42) = 8.0, P = 0.007] groups relative to the CTL. The IM group did not show significantly elevated ISD on any of these tasks. Thus, using the ISD measure of dispersion, all frontal groups except the IM group revealed greater ISD than the CTL. The NF group had significantly greater ISD than the CTL only on the Complex task.

**ICV**

The ICV was calculated for each subject within each task and group differences were investigated using contrasts to the CTLs. The mean ICV for each group on each task is presented in Fig. 3. ICV was significantly higher on the Easy task for the RDL [F(1,42) = 7.6, P = 0.009] and LDL [F(1,42) = 4.3, P = 0.045] groups relative to the CTL. ICV was significantly higher on the Complex task for the RDL [F(1,42) = 11, P = 0.002], SM [F(1,42) = 5.3, P = 0.03] and LDL [F(1,42) = 5.1, P = 0.03] groups relative to the CTL. ICV was significantly higher on the Redundant task for the LDL [F(1,42) = 6.6, P = 0.01] group relative to the CTL. There were no significant ICV differences for the IM and NF groups.

**Autocorrelation**

The correlation between RTs for adjacent trials was calculated for each subject and for each task performed on the first day. ANOVA (analysis of variance) did not detect differences between patient groups and CTL group in their lag-1 autocorrelation (P < 0.18).

**Factors affecting dispersion**

**Task complexity.** Because of the reported relationship of IIV to task complexity, repeated measures ANOVA was evaluated for the ISD across the Simple, Easy, Complex and Redundant tasks. As can be seen in Fig. 2, the profile across the four tasks for the control group was different from the profiles for the LDL [F(3, 123) = 3.5, P = 0.02] and NF [F(3, 123) = 3.2, P = 0.03] groups. Dispersion in the control group decreased from the Simple to the Easy task, whereas it increased in the LDL group. The NF group interaction was due to this group’s large reduction in dispersion from Complex to Redundant tasks. When this same complexity evaluation was completed for ICV (see Fig. 3), no significant differences between profiles were observed.

**Average RT.** We investigated the relationship between an individual’s average RT time and their SD deviation to see how RT affected IIV. ISD was modelled as a function of group, average RT, and the interaction between group and RT. Fig. 4 shows the slope estimates for each group’s regression of ISD on average RT for the Complex task across the range of individual average RT in each group and passing through the group’s grand average RT (the centre symbol on each regression line). There was little evidence for a relationship between average RT and the ISD in most groups. For example, the two medial (SM and IM) groups, the former
with notable IIV and the latter not, were most similar to the CTL group with respect to their relationship between variability and average RT. The LDL group, with the third fastest mean RT, showed the largest association between ISD and average RT ($b = 0.60$)—a significantly larger association than the CTLs [$F(1,36) = 5.7, P = 0.02$].

**Trends.** Slopes were calculated within each patient’s continuous stream of RTs for each task in an effort to detect any consistent speeding up (negative slope) or slowing down (positive slope) throughout the period that might affect any dispersion measure. Only the two lateral groups revealed significant slope differences compared with CTLs: the RDL...
group on the Simple task, with a negative average slope significantly different than the CTL group’s average slope $[F(1,41) = 4.6, P = 0.04]$; the LDL group on the Easy task, with a positive average slope significantly different than the CTL group $[F(1,42) = 6.1, P = 0.02]$, and on the Complex task, with an average negative slope significantly different than the CTL group $[F(1,42) = 5.3, P = 0.03]$.

**General effect of error rates.** We examined whether committing errors in the Complex task was related to increased variability. As already described, the LDL, RDL, SM and NF groups each had higher ISD than the CTL. In a previous paper describing the basic RT data for this experiment (Stuss et al., 2002b), the RDL group alone had a significantly lower sensitivity measure ($d’$) than the CTL group; i.e. they were impaired in discriminating targets from non-targets. In Fig. 5, average ISD and average $d’$ scores on the Complex task are plotted with the symbols for each group, and the slope of the effect of $d’$ on ISD for each group is illustrated with a regression line across the groups’ ranges. The two medial (SM, IM) and NF groups were not significantly different from the CTL. The RDL group showed a negative association between $d’$ and ISD, which was significantly different from the CTL group $[F(1,36) = 4.3, P = 0.045]$. The next largest association was in the LDL group.

**Local effect of errors.** Two RT differences were calculated in the Complex task, where the most errors occurred: the average change in RT before and the average change in RT after an error. Fig. 6 shows the average RT on trials with an incorrect response for subjects within each group who made at least one error. The average RT change from the correct antecedent response to the erroneous response and the average RT change from the erroneous response to the correct subsequent response are depicted with lines to the left and right of the symbol identifying each group (acceleration with a negative slope and deceleration with a positive slope). The normal profile is shorter RT on the error trials and longer RT on the trial after an error (Rabbitt and Vyas, 1970), as if recalibrating response speed. The IM group showed the expected profile before and after an error. Before an error, the SM group revealed slowing (although not significant, $P = 0.13$) on the erroneous trial. Three groups (IM, NF and control) showed the expected slowing after an error. The RDL group was somewhat flat before and after an error. The LDL group on average was 174 ms faster on trials after an error, which was significantly different from the control group $[F(1,35) = 5.0, P = 0.03]$.

**Summary**

Dispersion was assessed for the first test session allowing the full sample of participants to be included. All groups of frontal patients (except the IM group) had greater dispersion than the CTL. The NF group was significantly different from the CTL only on the Complex task, and only for ISD.
Different factors increased IIV in different lesion groups relative to CTL group. Increasing task complexity by adding a choice component to the reaction time affected ISD in the LDL and NF groups. An overall slow response time was associated with increased ISD in the LDL group. The LDL group was markedly faster on the trial after an error. An increase in error rate was associated with markedly increased IIV in the RDL group.

**Consistency across test sessions**

**Inconsistency of mean RT**

The first analysis compared the changes in mean RT over the 3 days. The DL group was more inconsistent in mean performance than the CTL group on the Simple [F(1,26) = 4.5, P = 0.04], Easy [F(1,26) = 7.0, P = 0.01], and Redundant [F(1,27) = 8.2, P = 0.008] tasks. The SM group was significantly more inconsistent than the CTL on the Redundant task [F(1,27) = 5.1, P = 0.03]. Inconsistency for the IM and NF groups did not differ from the CTL.

**Inconsistency of ISD and ICV**

These are described together since the results are almost identical for the two measures. The DL group was more inconsistent on at least one measure of dispersion (ISD or ICV) than the CTL group on the Easy [ISD, F(1,26) = 7.6, P = 0.01; ICV, F(1,26) = 2.0, P = 0.17], Complex [ISD, F(1,27) = 5.9, P = 0.02; ICV, F(1,27) = 11, P = 0.003] and Redundant [ISD, F(1,27) = 5.6, P = 0.03; ICV, F(1,27) = 4.4, P = 0.046] tasks. The SM group was more inconsistent in dispersion (ISD and ICV) than the CTL on the Redundant task only [ISD, F(1,27) = 24, P < 0.0001; ICV, F(1,31) = 5.4, P = 0.03]. The NF group was more inconsistent in dispersion relative to the CTL on the Complex task [ISD, F(1,27) = 3.8, P = 0.06; ICV, F(1,27) = 6.5, P = 0.02]. Again, inconsistency in the IM group was not significantly different from the CTL.

**The redundancy effect**

The Easy and Redundant tasks do not differ in actual difficulty even though the presence of three features in the Redundant task stimuli suggests an apparently greater complexity. Comparison of the Easy and Redundant tasks provides an index of the effect of irrelevant information in a stimulus. The difference between a subject’s speed on the Redundant and Easy tasks was more variable over the three assessment sessions for patients in the DL group relative to the CTL group [F(1,31) = 13, P = 0.001].
**Errors**

In a previous paper examining the RT and errors of the same patients on these tasks (Stuss et al., 2002b), we reported that the LDL group had decreased response bias (c)—tended to make primarily false positive errors—presumably a criterion setting problem. The RDL group, on the other hand, had decreased response sensitivity (d’)—made more errors of all types—presumably a problem differentiating targets and non-targets. The SM group exhibited an error pattern, in terms of bias and sensitivity, which fell in between the LDL and RDL groups. In this paper, we analysed whether bias and sensitivity changed over the three testing days. With the groups as defined, there were no significant differences from CTL subjects on any task on either d’ or bias (NF, d’, complex, \( P > 0.06 \)). Because of the potential importance of the regional differences within the frontal lobes (which by grouping both DL groups may have obscured any findings), we also analysed the original groups, even though the sample size was reduced. No group had significantly different inconsistency of sensitivity or bias compared with the CTL group. That is, the group impairment in bias (LDL) or sensitivity (RDL) was consistent from test session to test session.

**Summary**

Consistency of performance was assessed by comparison of measures over three assessment days. The consistency findings were interpreted compared with consistency in the CTL group. Normal consistency means that performance on one testing session on a given measure will as closely reflect performance on another testing session as the same comparison in the CTL group. There could be (and was) abnormal dispersion within a test session, but the dispersion could be (and often was) consistent between different test sessions. Dispersion and inconsistency are different measures of IIV.

The IM group did not show any inconsistency in performance. All other patient groups were inconsistent on many measures. The lateral (LDL, RDL) and SM frontal groups were inconsistent on considerably more measures than the NF group.

**Discussion**

There are four main conclusions from our study:

(i) Increased IIV may be caused by damage to specific brain regions. Lesions in the frontal lobes (with the exception of the ventral medial/orbitofrontal region) in particular impair stability of behaviour and led to increased IIV on the tests used here.

(ii) These fluctuations of performance in an individual are not simply error variance or statistical noise (Kelly et al., 2001). Individual differences, inter-trial fluctuations and inconsistency over repeated assessments are important measures of impairment.

(iii) There are different kinds of IIV. Not all types are elevated as a consequence of brain damage and different types of IIV are affected by damage in different brain regions. If disorders of stability of performance reflect impairment in top-down control, multiple mechanisms of control are disturbed.

(iv) Task factors have important effects on demonstration of variability.

**Lesion site effects**

IIV on RT tasks is significantly increased in most patients with frontal injury, but the effects are not uniform across all frontal regions.

Dispersion was highly associated with frontal injury (with the exception of the IM group) and was abnormal in the NF patients on the tests used here only for the Complex task ISD measurement. Thus, increased dispersion on RT tasks, measured by both ISD and ICV, is clearly more affected by SM and DL frontal lesions, even at a level of simple feature discrimination and choice. Dispersion is not a general effect of any brain damage, although task context may play a role (see below).

Analysis of lesion site effects on inconsistency could not be examined in such detail because of sample attrition secondary to the demands of three consecutive weeks of testing (see below). All of the patient groups, except the IM group, had some degree of inconsistency.

Task demands are likely to have an effect on whether IIV is observed or not after lesions in different regions. For example, the IM group revealed no IIV in the RT tasks used. Yet, in a study on the Wisconsin Card Sorting Test, this same group had difficulty staying on task (and thus were variable in a certain manner) under certain task conditions and not others (Stuss et al., 2000). The NF patients were variable when the task required three feature integration, such integration having been related to posterior brain regions (Bernstein and Robertson, 1998). There has been reported IIV after right and left brain injury related to neglect and lexical decision tasks, respectively (Anderson et al., 2000; Milberg et al., 2003). In future research, the potential impact of any frontal involvement in the patients examined, the differential impact of specific task demands (e.g. feature integration, visual spatial attention, language), general task complexity and the possible interactions of these factors should be investigated.

**Lesion and test factors affecting variability**

The effects of frontal lesions on IIV are complicated by interactions between lesion site and task factors, and the results of this study illuminate some of the reasons for conflicting results in past reports.
**Relationship between average performance and variability**

To investigate the impact of average performance on IIV, the ICV was used as one way of adjusting for the mean performance of the individual, and then comparing ISD and ICV results. A comparison of the ISD and ICV results across all tasks illustrated that dispersion measured as ISD was no longer significant when measured as ICV in the following cases: Easy RT: SM group; Complex RT: NF group; Redundant RT: SM group. Note that the SM group had the slowest RT and the LDL group among the faster.

A direct method of analysing the relationship between IIV and average performance is to compare the slope of ISD with respect to average performance within each group compared with the CTL. Only the LDL group was significantly different from the CTL in its association between individual variability and average RT. The SM group, with the slowest RT, showed the flattest relationship between ISD and performance, second only to the CTL.

There have been conflicting reports about the relationship between variability and mean performance, particularly in RT tasks. Some claim a direct relationship between mean RT and both diversity and dispersion (Hale et al., 1988; Salthouse, 1993); others demonstrate the relative independence of IIV from RT latency (Schwartz et al., 1989; Whyte et al., 1995; West et al., 2002b). Our results using the RT tasks in this study do not support a necessary relationship between an individual’s lengthening of RT and individual variability.

**Specifying complexity**

This is not transparent. In our study, the significant effects of complexity were seen in the comparison of Simple to Easy tasks in the LDL group only, with no additional effect into the Complex task. The step from constant stimulus–response mapping to any level of variable response appeared sufficient to elicit greater IIV in this susceptible patient group. In patients with left frontal injury, if the executive control system is already stressed, little complexity is required to produce failure of top–down control. In normal individuals, for a task to be complex enough to stress the executive control system, it must be much more difficult (West, 1999a).

**Trends**

Only the lateral groups showed significant differences in trends—the tendency to speed up or slow down over time. Drift will affect ISD and ICV. The fact that the SM group did not show significantly different slope suggests that several different factors may affect ISD and ICV in different groups.

**Errors**

There are effects of both the overall rate of errors and of the immediate neighbourhood presence of an error on dispersion. For the right lateral frontal group, an increase in the error rate was associated with increased dispersion (ISD). Analysis of RT pre- and post-errors as an index of executive control reveals a complex pattern: the RDL group was not abnormally affected by an error; the LDL group was faster after an error; and the SM group was much slower on trials with an error than the preceding trial. Different frontal regions contribute different mechanisms of control to the RT target behaviour.

**Consistency versus dispersion**

We tested a subset of the patients on three separate occasions over 3 weeks. All of the patient groups (excepting IM) had greater inconsistency, but the DL frontal patients were particularly inconsistent. The DL patients showed greater inconsistency than the CTL, had more instances of inconsistency than the NF group, and only patients with DL frontal pathology were inconsistent dealing with extraneous information on the Redundant RT task. Three assessments may not have been sufficient (especially with small groups) to uncover details about inconsistency, although Spikman et al. (1996), who reported increased IIV after TBI, noted that IIV actually diminished by the fourth block of testing. Consistency appears more robust than dispersion, in that it was not as affected by lesions as dispersion, but the investigation of consistency of performance is just beginning.

**Unaffected aspects of variability**

Not all indices of IIV are affected by brain damage. We did not find significant group differences in consecutive trial fluctuations, as assessed by autocorrelations. This measure denoted how much linear association there was between one trial and the next. We used autocorrelations to investigate trial to trial patterns rather than autocovariance because the former adjusts for inter-trial variability (Wei, 1990). That is, while the actual RTs among the groups may have differed, the fluctuations from trial-to-trial of individuals regardless of group were as stable as the CTL group.

**Regional brain lesions and variability**

Our first hypothesis was supported. Patients with frontal lesions do have greater IIV on these RT tasks than CTL subjects or patients with NF lesions, but the increased IIV is not seen uniformly. Patients with IM lesions have absolutely normal levels of IIV on the tasks used. The abnormal dispersion on ISD, which is not present with ICV, and only the occasional appearance of inconsistency in the posterior lesion group, who were comparable statistically with the CTL in most measures, indicates that increased IIV is not simply due to brain damage. To the best of our knowledge, our results (first presented in Stuss et al., 1999) are the first demonstration of a focal CNS cause of abnormal intra-individual variation. IIV is modulated by stimulus–response
control mechanisms (Rabbitt and Rodgers, 1977); and those control mechanisms for the execution of behaviours/responses are largely located in the frontal lobes. Whether this level of control is unique to the frontal lobes remains to be fully determined. However, in those studies that have demonstrated IIV after right or left hemisphere lesions, there is a need to dissociate the differential impact of frontal versus non-frontal involvement, and the relationship of the task demands (e.g. language) to the location of the lesion. It is possible that content-related variability may be more domain-specific and related to NF regions, with the frontal lobes contributing a more generic top-down control.

The second hypothesis was partly supported. Patients with right frontal lesions do have increased inconsistency, but so do the LDL and SM groups. The patients with lateral frontal regions may have a particular propensity to be affected by inconsistency of performance. The potential laterality and mechanisms of these effects need to be studied with a larger number of patients. The third hypothesis, that increased complexity would increase IIV in patients with frontal lesions, was supported and in an intriguing, not altogether expected, manner. No significant differences were found for either ISD or ICV in the Simple RT task, but significant differences were observed for the Easy task for all except the IM and NF groups. The critical step was introducing any complexity, i.e. going from Simple to Easy choice. When the effect of complexity was examined directly, the increased dispersion from the Simple to Easy tasks was observed in the LDL group. The fourth hypothesis was under-specified: a general presumption that errors would have a different effect on IIV in patients with frontal lesions than in CTLs. Although weak, the hypothesis was supported. Error feedback is one index of the control mechanism. If error analysis can be considered an indirect reflection of control mechanisms, this study demonstrates different disorders of control related to lesion location within the frontal lobes. Normal subjects maintain fast and accurate responses by dynamic response programming: error responses tend to be faster than correct responses, but after error detection responses slow as if recalibrating speed-accuracy limitations (Rabbitt and Vyas, 1970). To a greater or lesser degree, the CTL, IM frontal and NF groups exhibited this normal profile of response tracking with faster responses preceding errors, followed by slowing.

The RT of the RDL group was least affected by or after an error. This is compatible with our previous report (Stuss et al., 2002b) that this group showed the greatest impairment in sensitivity—defined as the ability to differentiate efficiently between targets and non-targets. Patients with RDL lesions have difficulty distinguishing what is important, and their lack of differential reaction to errors indicates low sensitivity to target. Low sensitivity and absence of change in response time after errors may underlie monitoring deficits after right frontal injury. In contrast to the CTL group, the LDL group had faster reaction times after the error. This suggests a deficit not in error detection (which would be reflected in minimal or no difference in RT as in the RDL group), but in error utilization (Konow and Pribram, 1970), as if attention were captured by the error. A seemingly similar and selective LDL frontal deficit was reported in our earlier study (Stuss et al., 1999) using an Inhibition of Return paradigm. The left frontal group in that study showed facilitation rather than inhibition of return.

The SM group was slower on trials with an error, but after the error, there was no additional slowing. This result suggests that the patients in the SM group were alerted by committing an error. We have proposed that the fundamental impairment caused by damage to the SM areas is maintaining response activation or energization. We have demonstrated blunted activation in this group on numerous tasks: the Stroop test (Stuss et al., 2001), verbal fluency (Stuss et al., 1998) and Simple RT (Stuss et al., 2002b). The current error feedback results strongly support this view. SM damage causes loss of activation over time and RT becomes slower. Then, with an external warning stimulus (the error), arousal or effort necessary to maintain that level of activation is restored—at least temporarily. In clinical reports, this behaviour has been labelled ‘drifting attention’ (Stuss and Benson, 1986).

A tentative model: effects of specific frontal lesions on IIV

Lesions in the SM region disrupt maintenance of activation to respond and of energization of various schemata in the response set (see also Stuss et al., 1995). Thus, lesions in the SM region cause significant dispersion and inconsistency compared with CTLs that is not simply due to errors or speed, even though this group was the slowest of the patient groups.

Lesions in the RDL region impair sensitivity—the ability to differentiate the correct stimulus. Thus, patients with RDL lesions make multiple errors and, in this group, it is the overall error rate that is associated with IIV. The effect of a particular error on the surrounding trials is weak as the patients are relatively insensitive to errors.

Lesions in the LDL region impair establishment of criteria for functional response. Thus, dispersion is high, and complexity and, probably to some degree errors and inconsistent bias, all combine to increase IIV. This was the one group in which the RT slowing was related to variability, even though this group was among the faster patient groups.

The IM group had normal IIV. If variability is related to executive control of the deployment of attentional resources, of activation to respond and to maintenance of sharp criteria (‘if-then’ operations) as in our earlier model (Stuss et al., 1995), then IM regions apparently do not contribute to this deployment. On a much different task, the Wisconsin Card Sorting Test (Stuss et al., 2001), when patients in the IM lesion group were made explicitly aware of their on-going performance, they—uniquely among frontal injured patients—appeared to lose track of what they were doing. This may be a different type of variability of performance at the level of simultaneous attention to accuracy and to feedback.
The model that we propose requires several caveats. To insure that the basic RT task could be performed at a high level, we excluded patients with significant aphasia or neglect. When a task has high verbal demands, there may be high IV introduced by aphasia. When a task has high perceptual demands, visual neglect may inject IV. Increased IV on domain-specific tasks is likely with lesions that disrupt performance within those domains and has been demonstrated for spatial neglect. Our results cannot be reduced to differences in demographic variables, although these may have some effect. For example, simple attentional problems cannot explain the patterns of group differences. The LDL and the RDL groups had lower forward digit span, but not the SM group. Since these are the three groups which displayed the most variability, it is unlikely that digit span scores were a primary contributor to IV. Age differences from the CTL group were observed for NF, IM and LDL groups, of which the former two were not variable. Differences in education or intelligence are not likely to have a major impact, as there were no significant differences between the CTL group and any of the patient groups for the dispersion measures.

Secondly, we are also aware and have published on the possible effect of time of day on variability (West et al., 2002a). Our subjects were studied at different times of the day, depending on their availability but there was no systematic bias across groups. However, for the repeated testings, time of day was kept constant for the individual subject—thus controlling for that factor within each participant for the consistency measures.

A third caveat concerns the distinction between frontal lobe lesions and frontal system lesions. This report focused on patients with focal frontal lobe lesions, but there are extensive cortico-cortical and frontal-subcortical connections (e.g. Nauta, 1971, 1973; Wiesendanger and Wise, 1992; Petrides and Pandya, 1994, 1999) that may support performance capacities. Damage to focal frontal regions or to NF regions such as basal ganglia (Cummings, 1993) or cerebellum (Holmes, 1939; Bastian et al., 1996) may produce similar deficits in executive function. A similar proposal of ‘frontal lobe’ dysfunction has been made for the increased IV reported in normal elderly people (West, 1999b; West et al., 2002b). Frontal lobe dysfunction has also been proposed to account for the increased IV noted in TBI (thought to affect the integrity of the frontal lobes) individuals (Stuss et al., 1989, 1994b).

A fourth caveat is the fundamental claim that there are properties of top–down regulation of attention that are instantiated in frontal structures (and their connections). There is a litany of impairments associated with frontal injury that might be recruited to account for our findings: reduced sustained attention; poor working memory; perseveration; failure to inhibit responses; and poor action planning or strategy formulation. It is likely that some of these putative deficits do play a role in overall performance, but none seems adequate to account for the general results on RT or to the specific findings for IV. With regard to sustained attention, we demonstrated that there were no consistent changes in the slope of performance over time. It may be that the fluctuating ‘top–down’ attention that we have reported is a partial explanation for impaired sustained attention in some groups rather than the opposite. With regard to working memory, the tasks have low demands on working memory as they are blocked, require no response shift demands during blocks, and show no consistent relationship between potential complexity that might increase ‘keeping in mind’ burdens. With regard to perseveration and failure to inhibit responses, these terms are surface descriptions of error types more than basic processes. Our patients made errors of these types, but there was no consistent relationship between errors and IV except in the RDL group. There may be multiple routes to perseveration and failure to inhibit depending on task, and we have demonstrated this in other studies (Stuss et al., 1999, 2000).

With regard to strategy formation, patients with left DL and right DL lesions surely do have impairments in strategy formulation. In this and other reports (Stuss et al., 1994a, 2002b; Alexander et al., 2003), we have demonstrated that patients with left DL lesions adopt a strategy of shifted bias and that patients with right DL lesions adopt a strategy of reduced sensitivity. Those strategies account for the nature of their errors, but not the variability in their correct responses. In this experiment, only the redundant task offers the possibility of creating a strategy during the stimulus presentations, that is, once the redundancy is detected. There may have been an interaction between strategy and variability in that task.

Rather than account for ‘micro-behaviours’ such as fluctuating attention with ‘macro-behaviours’ such as perseveration or inhibition failure, we prefer to demonstrate a range of micro-behaviours that, depending upon varied and distinctive patterns of recruitment, add up to the various macro-behaviours. In the original outline (Stuss et al., 1995) of this modified form of the Norman and Shallice (1986) theory, we proposed a number of forms of attention, all under the control of frontal structures, which are differentially recruited under different cognitive contexts to produce the coarser behaviours that are commonly considered ‘frontal lobe functions’.

**Clinical implications**

There is a very significant implication of these data. A patient’s mean performance at one time may not reflect wide irregularities over time and thus a single clinical assessment of a patient with a frontal lesion may not capture dispersion or inconsistency. Success in real-life tasks may depend as much on predictability and consistency as on average performance.

Can dispersion and inconsistency be reduced? Bleiberg et al. (1993) administered dextroamphetamine in a single subject placebo crossover design to an individual with TBL. On treatment only, variability decreased, but only the SDs were reported, so the relationship to overall RT speed is unknown. Verbal self-regulation (Luria, 1966) may be
effective for tasks that unfold at a slower pace than RT tasks. It was successful in reducing motor impersistence—a disorder most commonly found after focal right frontal pathology that has some similarity to IIV (Stuss et al., 1987).

The results of this study suggest a method to develop behavioural interventions: specify a patient’s lesion location with appropriate imaging, then identify the systems involved (i.e. SM or left dorsolateral, etc.), then assess the specific form of IIV through appropriate assessment. Patients with injury in SM regions and the profile of variability demonstrated here might respond to alerting cues to maintain appropriate activation. Patients with RDL lesions might utilize explicit feedback to monitor their performance by distinguishing better between targets and non-targets. Clarifying the relationship between specific lesion sites and specific basic processes of attention should lead to more specific rehabilitation procedures and provide a base for research efforts in rehabilitation.

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