Virtual reality investigation of strategy formation, rule breaking and prospective memory in patients with focal prefrontal neurosurgical lesions

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ABSTRACT

Planning and organisational ability was investigated in 35 patients with prefrontal lesions, using virtual reality (VR) to mimic everyday activity, but in a laboratory setting. A multi-componential VR procedure, the Bungalow Task was developed to test strategy formation, rule breaking and prospective memory. The task involved simulation of decision-making whilst a participant moved around a virtual bungalow, selecting furniture for removal according to specified instructions, and various aspects of prospective memory were tested. Significant strategy formation and rule breaking impairments were observed and additional time and activity, but not event based prospective memory impairment observed. The study demonstrates the successful use of VR as a neuropsychological tool for investigating executive functioning in an ecologically valid fashion.

1. INTRODUCTION

Virtual reality (VR) approaches to neuropsychology offer the prospect of simulating real life activities and this has a number potential uses; for example, assessing neuropsychological impairments in a fashion that bridges the gap between deficit and everyday disability; and also engaging patients in neuropsychological rehabilitation in a 'trial' fashion, so as to build up behavioural skills without the initial complication of engaging the patient in hazardous activity. Despite this, there have been relatively few developments in this area and there are many VR procedures could be developed to benefit this field.

One such area is to assess executive functioning in patients with various forms of brain damage. The term 'executive functioning' refers to the sequencing and organisation of behaviour, and incorporates a variety of cognitive processes, including planning, strategy formation and mental flexibility. The neural basis of such abilities have been strongly linked to the prefrontal cortex, with damage in this area resulting in respective behavioural impairment. Traditional tests of executive functioning have been developed and these are used in the routine assessment of patients.

Nevertheless, there is a growing consensus for the need for tests of executive functioning that are closer to 'real world activities' if they are to be useful in predicting patient disability. This was highlighted initially by Shallice and Burgess (1991), who investigated three patients with frontal lobe damage who performed normally on established executive functioning tests but demonstrated disorganised behaviour in everyday life. To try to capture the latter experimentally, they designed the Multiple Errands test in which they took their patients into a city street and required them to conduct a number of errands. For example, they had to buy certain items such as a brown loaf and a packet of fruit pastilles. More complex tasks were also included, such as obtaining the necessary items to send a postcard and certain fact finding errands. They also built certain rules into the test, such as having to spend as little money as possible. This test proved very sensitive to executive impairment in these patients, a finding that has been replicated by Goldstein et al (1993) in a single case study of a patient with a focal frontal neurosurgical lesion. Such experimental studies have also

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given rise to standardised tests such the Zoo Map test and the Modified Six Elements test, which are now in routine clinical use (Wilson et al., 1996), but which try to simulate everyday activity through laboratory tasks. For example, the zoo test involves presenting the patient with a map of a zoo and giving them the instructions that they have to trace round the zoo (using a pen), visiting certain locations and not repeating some of the routes.

Other approaches have focused specifically on planning ability. This includes the VIrtual Planning Test developed by Miotto and Morris (1998). This is neuropsychological test in the form of a board game in which participants are required to carry out a number of actions within four fictional days. They have a planning board, with various activities arrayed in front of them, each activity presented as action instruction on a 'chip.' For each day, they have to select four activities and by the end of the four days they have to have completed a number of target activities as specified on a cue card. To make the task more akin to everyday life, some activities have to be completed at or by a certain time within the period; some relate to a fictional trip abroad at the end of the four days, with others not related to this trip; some are preparatory and have to be completed in order to start other activities. Additionally, distracter times were provided to lure the patients away from the required activities. This task showed an overall impairment in the efficiency of planning in a group of patients with focal frontal lesions. It also showed they were prone to fail on more isolated activities and select distracter items which were related more immediately relevant to the patients current context.

The development of such tests has created a dilemma in terms of tasks design. If the task is made interactive and involves real world activity, such as the original Multiple Errands test, it can be too long and costly to administer, and is not possible to standardise other than for local use. On the other hand, if the tasks are simplified into the form of paper and pencil or board games, they potentially lose their degree of ecological validity and, possibly, sensitivity to neuropsychological disability. Virtual reality procedures may help solve this dilemma by bringing real world tasks back into the laboratory.

This paper describes the use of such an approach to investigating planning and organisational ability in patients with focal frontal lesions. The task, termed 'the Bungalow' is a virtual reality construction of a four-room bungalow, which the participant can navigate around with the aid of a joystick. The participant is given a scenario in which they are the imaginary removal person and have to collect furniture in specified manner. The task was developed specifically to measure planning ability in a way that tapped into certain key aspects. This included:

(1) The ability to develop strategies: Such ability increases the efficiency of task completion and often occurs spontaneously on tasks that can benefit from the use of strategy. Frontal lobe patients have been shown to have strategy formation deficits on a variety of procedures (eg. Owen et al., 1990; Miotto et al., 1996);
(2) The ability to follow task rules: Rule breaks are a common feature of executive dysfunction and have been shown to occur on various neuropsychological procedures, including the Multiple Errands task described above;
(3) Prospective Memory: Remembering to execute activities at the appropriate moment is a key aspect of everyday executive functioning. This involves the laying down of markers, which are then used to 'trigger' activities at the appropriate time. Hence prospective memory is an integral aspect of the execution of plans. Patients with frontal lobe damage have been shown to be impaired in this function (Coburn, 1995).

As will be described below, these different aspects can be incorporated into one overall test, whilst maintaining the complexity and naturalistic aspect of a virtual reality test. In order to validate such a task, it was tested on a large group of patients who had undergone frontal lobe neurosurgery and where, in the past, similar cohorts of patients have shown specific neuropsychological deficits relating to executive functioning (Morris et al., 1997a; b; Miotto et al., 1996; Miotto and Morris, 1998).

2. METHOD

2.1 Subjects

35 patients who had undergone prefrontal lobe neurosurgery were included in the study. Sixteen patients had lesions restricted to the right frontal lobe (males and females), fourteen had left-sided frontal lesions (males and females), and five underwent bifrontal removals (males and females). In terms of the etiology, in the

right group there were eight cases of resections for treatment of pharmacologically intractable epilepsy, six cases of tumour removal (four meningiomas, one carvenoma, and one metestatic tumour), and two cases of anterior communicating artery (ACoA) aneurysm clippings subsequent to rupture and subarachnoid haemorrhage. In the *left* frontal group seven cases had undergone neurosurgical intervention for pharmacologically intractable epilepsy, six had tumours removed (two cases of meningiomas, one astrocytoma, one ependynoma, and two oligodendrogliomas II), and one patient had a lesion due to multiple aneurysms. The cases comprising the *bifrontal* subgroup had all undergone neurosurgery for the removal of meningiomas. They were matched approximately for age and National Adult Reading Test estimated IQ with a control group of 35 subjects (respectively: Age Frontal: mean = 42.2, S.D. = 12.7; Controls: mean = 42.3, S.D. = 12.3; IQ Frontal: mean = 106.8, S.D. = 11.2; Controls: Mean = 108.4, S.D. = 10.7).

Figure 1. *The Bungalow Task showing hallway (top) and four rooms (bottom four panels).*

2.2 Virtual Reality Test

The Superscape VRT software package was used to construct the virtual environment and programmed by Third Dimension Ltd, UK. The test run a on PC fitted on a Vivitron Monitor and a Microsoft Sidewinder joystick. To move within the environment of the task, lateral movement of the joystick produced rotation of direction and forward or backward movement, a respective forward or backward locomotion.

2.3 Procedure

The procedure, termed the *Bungalow Task*, consists of a virtual reality representation of a bungalow, with four main rooms and a hallway (see Figure 1). The participant is told that they are a 'removal' person and that they have to enter the bungalow and select furniture or miscellaneous items that have to be moved to another house. A number of rules are provided that dictate the manner of removal. Specifically, the participant has to collect the items for a particular room in the new house first (the lounge). The items for this room may be distributed around the different rooms of the bungalow, so the participant has to go through them in turn. They then have to repeat the process for a different room (the dining room) and so on until all the rooms in the new house have been considered (nursery, kitchen, music room, study, bedroom and hallway). The participant moves around the bungalow, controlling their movement with the aid of the joystick and selects items by pointing to them on the Monitor, at which point they disappear.

Built in to the test are a number of tests of prospective memory. This includes: (a) *Activity related*: Here the participant has to remember to shut the front door on entering the bungalow and they should always shut the door when they exit room two; (b) *Time related:* They are told that a van is coming to the front door to take the selected furniture. The 'doorbell' is not working, so they should visit the front door every five minutes. They are provided with a clock and updated time of arrival of the van for every five minutes; and (c) *Event related*: Arranged round the rooms are specific items of furniture that contain glass. When encountered, these should not be selected for removal but should be labelled with a 'fragile' notice.

To facilitate memory for the instructions, the participants are provided with a cue card that summarise the instructions. Additionally, to ensure understanding, the participants had to explain back to the experimenter the rules of the procedure and seek clarification where necessary. There was no time limit for the test, but the overall time taken to complete was recorded. In all, 31 items were positioned in the bungalow, including the 'fragile' and 'non-fragile' items.

2.4 Measures

The task has two overall measures, the time taken to complete the instructions and the number of rooms visited. In addition, there were measures of strategy formation, rule breaking, strategy formation and prospective memory as follows:

Strategy Formation: Piloting of the task revealed that the pattern of room search follows a set sequence or strategy. The dominant form of this is to visit rooms 1, 2, 3 and 4 in order collecting all the furniture for one category, and then going through the rooms again in this order for the next category, until all have been completed. In addition, a different search path was identified in some participants, with the order rooms 1, 3, 2 and 4. In order to quantify strategy formation, the search path was scored according to the degree of displacement from either the 1,2,3,4 or 1,3,2,4 sequences, with three points given for the zero displacement. The data were scored according to both search path models and the maximum score obtained by a subject used as the measure of strategy formation.

Rule Breaking: This relates to failing to select the categories of furniture in the right order, as specified by the instructions and the cue card. To obtain a score, a point is given every time a category is followed by the correct one, the measure having a maximum score of seven. The order of categories of furniture collection is obtained by following the series of responses and ascertaining when the type of furniture collected switched to a new category. Additionally, two types of intrusion errors were recorded, namely, going back to a category when this had already been attempted either during the series of categories or when all the categories had been used. These types of errors are referred to respectively as Intrusion Error types I and II.

Prospective Memory: For these measures, the following scoring systems were used: (a) *Activity related*: A point was awarded if they succeeded in shutting the front door on entering the building. For the requirement to shut the door when exiting room 2, a point was awarded when this happened and the total score divided by the number of times room 2 was entered, with the result multiplied by 100 obtain a percentage: (b) *Time related*: Here, the target time for opening the front door was subtracted from the time they reached it, with a positive value indicating the amount of time they were late and a negative score the degree to which they were early. Additionally, this data were unsigned to obtain an overall indication of accuracy irrespective of being later or early: (c) *Event related*: The number or times an 'fragile' item of furniture was labelled was recorded and divided by the total number of furniture items that were either labelled or selected for collection.

3. RESULTS

Table 1 shows the total time that the patients and controls took to complete the bungalow task, indicating that there was no difference overall. In contrast, the patients visited significantly less rooms ($t(51.09)=4.27$, $p<0.001$).

Table 2 provides the rule breaking data. A non parametric analysis showed the frontal group made significantly more errors than the controls overall ($x^2=13.03$, df=3, $p<0.01$). There were also significantly more Intrusion Type I errors (x^2=15.58, df=3, p=.001), but no difference in Intrusion Type II errors, these type of errors being infrequent.

Table 1. *Total time taken and number of rooms visited (standard errors are given in brackets).*

	Frontal Lobe Patients Mean (S.E.)	Controls Mean (S.E.)
Total Time	19.73 (1.27)	20.52 (1.25)
Rooms Visited	20.46 (1.55)	27.91 (0.80)

Table 2. *Rule Break and Intrusion Errors (standard errors are given in brackets).*

	Frontal Lobe Patients Mean (S.D.)	Controls Mean (S.D.)
Rule Breaks	5.31 (0.44)	6.94 (0.05)
Intrusion Type I Errors	3.11 (0.72)	0.54 (0.19)
Intrusion Type II Errors	0.94 (0.37)	0.20 (0.05)

Table 3 shows the strategy formation results, with a significant impairment in the frontal lobe patients ($F(2,66) = 6.47$, $P<0.001$). Examples of strategy formation impairment are given in Figure 2, which shows the more haphazard pattern of searches in two individual patients, contrasted against the main strategy order. This type of pattern was found frequently in the patient group and varied in extremes of disorganisation.

Table 3. *Strategy formation scores (a high score signifies a good strategy).*

	Frontal Lobe Patients Mean (S.D.)	Controls Mean (S.D.)
Strategy Score	23.71 (1.65)	31.74 (0.91)

Table 4 shows the prospective memory results. For the activity based measures, there was no impairment in the frontal lobe group. For the time based test there was a highly significant difference in the unsigned measure ($t(68) = 4.07$, $P <0.001$), and this reflected the patients being overall late in terms of reaching the front door on time ($t(68)=3.77$, $P < 0.001$). For the event related test, the patients selected significantly fewer of the fragile items ($t(68)=2.23$, $P<0.05$).

Table 4. *Prospective Memory Scores (standard errors are given in brackets).*

	Frontal Lobe Patients Mean (S.D.)	Controls Mean (S.D.)
Activity based – front door	0.69 (0.07)	0.54 (0.08)
Activity based – room two	73.01 (5.41)	81.08 (2.93)
Time based – unsigned (sec.)	76.18 (9.42)	31.72 (5.51)
Time based – signed (sec.)	62.27 (10.88)	14.30 (6.55)
Event based	3.19 (0.33)	4.10 (0.25)

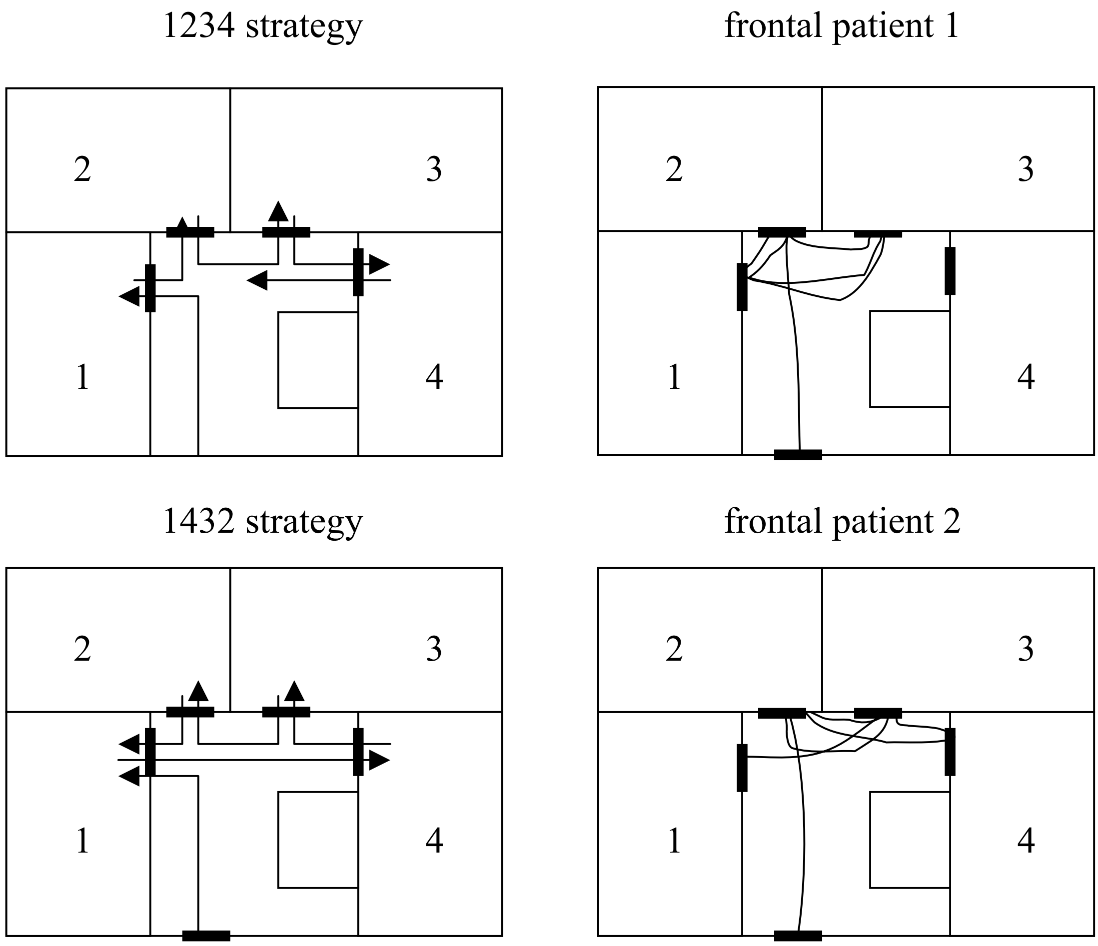

Figure 2. *The dominant path strategies on the bungalow task and examples or poor strategy two frontal lobe patients*

4. DISCUSSION

The Bungalow procedure was successful in providing an assessment procedure for the frontal lobe patients. All patients were able to follow the basic procedures and navigate around the bungalow, responding by selecting objects. Also, despite the multifaceted nature of the test, they were able to understand the rules, with part of the training procedure requiring the participant to explain back the procedures to the experiment, with the aid of the cue card. The patients also completed the task in the same amount of time as the controls, although they visited less rooms and showed less efficient strategies, increased rule breaks and impairments in prospective memory

A significant increase in rule breaks is characteristic of frontal lobe damage (Goel and Grafman, 1995) and the current procedure shows how this can be systematically measured using a computerised procedure. In this case the rule breaks consisted of not following the instruction to collect a particular category of furniture first before moving on to the next one. Here it is clear that the instructions were well understood and the procedure relatively simple, as indicated by the near perfect scores for the controls. In contrast, the patients showed a clear deficit as a group. Additionally, they also had a tendency to interject their collection of a particular category by going back to items not collected for previous categories (Intrusion type I errors). This reflected the more chaotic organisational style of the patients in general, where searching the categories was not so clearly delineated. The other type of intrusion error (type II) was going back to collect previous category items at the end of the series of searches. This is, in a sense, an ameliorative strategy, since it is required to finish the overall task. However, despite being less efficient in collecting the times, they did not show an increase in this type of response.

The task also elicited impairments in strategy formation, in which the frontal patients moved around the different rooms in less organised fashion than the controls. Such strategy formation impairment has been observed previously on spatial search tasks such as the spatial working memory task (Owen et al., 1990; Miotto et al., 1996), and shows failure either to develop a strategy to apply it systematically. Inspection of individual participant data suggested that the problem lies with sustaining the strategy since, the initial search path showed patients were demonstrated successfully the model strategies. In the current case, the strategy relates to a 'real life scenario' since many everyday tasks require 'parsing' in this fashion, with appropriate efficient approaches to reduce the amount of effort involved. In this sense, the Bungalow task shows how it is possible to bridge the gap between laboratory based procedures and everyday behaviour.

Finally, various prospective memory tasks were built into the procedure. These are made more realistic than many laboratory tasks, in that the background task (collecting the furniture), simulates something akin to everyday activity, and the foreground task requires a form of memory familiar to everyday life (e.g. remembering to close doors or looking out for someone coming). Three types of prospective memory were explored and the results suggest a particular pattern of impairment. No deficit was seen with the activity related memory and this may relate to fact that when moving through a door there is a strong associative link between opening the door and remembering to close it, such that the required activity is heavily cued. For the time related activity, where the participant had to remember to arrive at the door at the correct time, the frontal lobe patients did show a deficit, being significantly late as a group. Here the appropriate activity has to be 'internally generated,' with continuous time monitoring and this deficit is fairly typical of reports of everyday behaviour of such patients. The intermediate result with the event related task, where the fragile furniture had to be labelled, with a smaller, but significant deficit may represent the fact that, although the furniture cues the response, this may be a less well established association than the one of opening and closing doors.

This study points the way towards developing more ecologically valid tests to planning an organisation that have potential to be used for routine clinical assessments, with advantages of simulation, and demonstrated test sensitivity. Future procedures can be more finely honed into clinical tests, perhaps shorting the length, and combining with tests of other types of functions. Further developments in this area should lead to a range of clinically validated tests for use in elucidating neuropsychological impairment.

5. CONCLUSIONS

In conclusion, a virtual reality has been used to test executive functioning in patients with focal frontal lesions. This procedures used are shown to be sensitive to impairment and elucidated a pattern of impairment in terms of rule breaks, strategy formation deficit and impairment in time based and event based prospective memory. The advantages of this approach from an experimental point of view have been discussed, with the clear finding that this experiment validated the use of this technology for testing executive function.

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