Pilot results from a virtual reality executive function task

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Abstract—**Impairments in executive functions (EF) negatively impact the capacity for independent living, damaging personal autonomy, and diminishing quality of life. Virtual environments offer an ecologically valid way to evaluate a person's ability to carry out tasks that depend on EFs. The purpose of this pilot study was to evaluate the feasibility of a virtual reality office task, the Assessim Office (AO), in persons with Multiple Sclerosis and Traumatic Brain Injury, to evaluate performance of patient groups relative to each other and to healthy controls on the AO, and to explore the relationship between patient's performance on AO tasks and neuropsychological measures of EF.**

Keywords — virtual reality, executive functions, traumatic brain injury, multiple sclerosis

I. Introduction

Executive Functioning (EF) is a multifaceted construct that supports the formation, maintainenance and shifting of mental sets. Although EF is a widely recognized term, it is often conceptualized and operationalized differently among researchers. Within clinical neuropsychology, there are a handful of skills and processes that are widely recognized as elemental within EF. Skills include planning and reasoning, organizing, and problem solving; processes include working memory, selective attention, attentional vigilance, divided attention and inhibition of irrelevant information [1, 2]. Skills and processes are integrated into complex goal-directed and purposive behaviors that are requisite for successful execution of daily life functions. EF impairments negatively impact the capacity for independent living by decreasing personal autonomy, impeding return to employment and community, and diminishing quality of life [3, 4]. The accurate evaluation of these impairments is important in order to assist clinicians in treatment planning.

The traditional approach to evaluating EF impairments is through paper and pencil neuropsychological evaluations. However, patients who are expected to perform poorly due to self-reported difficulties with daily activities may actually perform within normal limits on standardized neuropsychological tests of executive functioning [5-7]. Indeed, studies have demonstrated that the relationship between performance on paper and pencil EF tasks and performance in activities of daily living is weak [8, 9]. These discrepancies suggest that standardized paper and pencil neuropsychological tests may not adequately reproduce the complexity and dynamic nature of real-life situations, resulting in limited meaningfulness, practicality, and generalizability to activities of daily living for patient populations. Ecologically valid tools must be capable of taxing multiple executive processes simultaneously (e.g., increasing stressors and distractions) to be more predictive of real-world performances [9-11].

Virtual environments allow for the creation of testing instruments that are able to adequately detect dysfunction in specific cognitive domains while providing greater ecological validity than some traditional neurocognitive batteries [12]. Research has demonstrated that performance using VR-based measures of learning and memory are correlated with neuropsychological measures of memory ability [13, 14] and similar findings have been documented between VR-based measures of EF and neuropsychological measures of EF [e.g., 15]. Further, studies investigating computer-based cognitive assessment instruments have shown that virtual reality can be used as an effective tool to predict everyday task performance in individuals with neurological impairment [13, 15, 16]. Therefore, further research into the development of such virtual-based testing instruments is particularly helpful for improved elucidation of traditionally complex cognitive impairments.

The application of virtual environments to the evaluation and treatment of EF impairments has been gradually increasing over the last decade. EF skills and processes targeted through existing studies include prospective memory, planning, organizing, problem solving, attention shifting, and sense of presence [2, 15, 17-26]. Some of these efforts produced isolated publications, which served largely to establish feasibility and usability of specific virtual EF evaluation tools. However, there are three virtual environments (i.e., Virtual Action Planning - Supermarket (VAP-S); Virtual Mall (VMall); Virtual Library Test (VLT)) wherein the research has moved beyond ascertaining feasibility, and the investigators have sought to establish ecological and construct validity [15, 20-26]. The VAP-S is a supermarket developed to assess cognitive planning ability. It has been established as effective in differentiating various patient groups (i.e., mild cognitive impairment, Parkinson's disease, schizophrenia, and stroke) from healthy controls (HCs) [20-22, 27]. The VMall is a virtual supermarket

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environment, utilized to evaluate and treat deficits in planning, organizing, multitasking and problem solving. The VMall has been found to demonstrate ecological and construct validity as an evaluation tool in stroke [23, 25] and to be effective in improving complex everyday activities in acquired and traumatic brain injury [24, 26]. The VLT evaluates prospective memory performance in a virtual library setting. Findings supported the convergent and discriminant validity of the VLT applied in a TBI population [15].

Overall, studies to date have demonstrated strong preliminary evidence of the advantage of using virtual environments for the evaluation and treatment of EF impairments. EF is multifaceted, however, and existing studies have not yet addressed all of the skills and processes comprising EF. The Assessim Office (AO) was devised to complement the existing body of work and to capture elements of EF not yet addressed in current virtual environments. The AO evaluates performance on tasks of selective and divided attention, complex problem solving, working memory, and prospective memory [28]. The goal of this initial pilot work was to evaluate the feasibility of using a virtual reality-based evaluation tool in individuals with traumatic brain injury (TBI) and multiple sclerosis (MS), to assess the performance of the patient groups relative to each other and to healthy controls, and to explore the relationship between patients' performance on the AO and on standardized EF measures. Subsequent studies will evaluate the ecological and construct validity of the AO.

II. METHODS

A. Participants

The study sample included seven individuals with TBI (age = 40.1±15.3; education = 14.3±1.8; 3 male), five individuals with MS (age = 51.0±8.9; education = 14.6±2.0; 1 male), and seven HCs (age = 31.1±14.1; education = 16±1.2; 4 male), for a total of 19 participants. There were no significant group differences in age or education. Both patient groups were enrolled in clinical trials evaluating the effectiveness of behavioral interventions in improving cognitive function and completed a comprehensive neuropsychological evaluation as part of their participation in each respective study. HCs were recruited specifically for evaluating their performance on the AO for comparison to that of the patient populations.

B. Measures: Assessim Office

The Assessim Office (AO) task is a comprehensive VR framework for the assessment of cognitive functions, developed in collaboration with the University of Southern California's Institute for Creative Technologies and the Kessler Foundation Research Center. The application is based on the Assessim Framework and provides a range of realistic tasks for the assessment of cognitive abilities. Although the AO environment takes place in a work setting, the aim of the application is to assess EF in a complex functional environment. The combination of several tasks of different priorities (e.g. rule-based decision task, reaction time task, divided attention task) is designed to simulate challenging scenarios that are similar to the demands that are placed on the cognitive system in a real-world work setting.

The developed framework encompasses a virtual office environment and the software infrastructure to rapidly implement cognitive tasks anywhere in the virtual scenario. The AO was developed using iterative design and testing [28]; through more than 20 iterations, we tested and adjusted input devices, user interfaces, task difficulties, data collection algorithms and consumer instructions (See Koenig, et al., 2012 for a thorough review of the development process).

In order to facilitate standardization of the administration of AO tasks, manualized instructions were created to accompany the software and assist the examiner. The manual includes a list of questions frequently asked by participants, along with the standardized responses to be given in different situations. For example, if the participant asks, "Can I use the shredder"; the examiner would respond, "Remember to focus on completing the tasks on your priority list. These tasks are time-sensitive and should be completed as quickly as possible". The manual also provides cues for common confusions. For example, if the participant becomes lost in the office environment, initial cueing is, "Are you looking for something?" Depending on the participant's response, additional detailed cueing is provided to ensure that AO is measuring the participant's ability to carry out EF tasks instead of spatial orientation.

C. Measures: Neuropsychological Assessment

TBI and MS participants were evaluated with a comprehensive battery of standardized paper and pencil tests designed to measure various domains of cognition, including, but not limited to attention, memory, speed of information processing, and intellectual and executive functions. Only the measures of complex attention and executive function were examined for the purpose of this study (Table 1).

D. Procedures

All studies were approved by the Institutional Review Board (IRB) of Kessler Foundation. All participants signed an informed consent approved by the Kessler Foundation IRB prior to enrollment and participation in the respective study. Participants in clinical samples received the AO as part of a

TABLE 1. NEUROPSYCHOLOGICALASSESSMENT OF EXECUTIVE FUNCTION

Test	Neuropsychological Construct
WAIS-III Letter Number Sequencing (LNS) [29]	Working memory, mental control
WAIS-III Digit Span (Backward) [29]	Working memory, complex attention
Delis-Kaplan Executive Function System (D-KEFS) Trails Condition 4 [30]	Executive function (set switching, flexibility of thinking)
D-KEFS Color Word Test (Inhibition and Inhibition Switching Conditions) [30]	Executive function (response inhibition, flexibility of thinking)
Wechsler Abbreviated Scale of Intelligence (WASI; Block Design and Matrix Reasoning) [31]	Executive function (complex problem solving, abstract reasoning)

comprehensive neuropsychological evaluation. HCs were recruited for the sole purpose of comparing their data to patient populations and did not undergo any other neuropsychological testing.

All participant groups (i.e., MS, TBI, HC) were administered the AO on an IBM PC-compatible computer with a standard 24-inch LCD monitor and plug-and-play stereo desktop speakers. Participants were seated at least 50 cm away from the screen and navigated the virtual environment and completed virtual tasks using the left and right keys of a two-key mouse.

Participants worked in the virtual office environment, where they were seated at the virtual desk equipped with a computer monitor, a keyboard, a counting device to track the budget, a document tray, and a file folder. The virtual office environment also included other desks, two printers, and a conference room with a projector screen (See Fig. 1 for a screen shot of the AO environment). Prior to beginning the experimental task, participants were oriented to the location of key objects in the virtual office environment. They were able to practice navigating through the environment, and were trained on which tasks they would be asked to carry out during their workday. Multiple attempts to review screen shots and task instructions were given as necessary. Participants were told their workday would last approximately 15 minutes.

Participants were asked to complete the following tasks during the workday: 1) respond to emails, 2) decide whether to accept or reject real estate offers based on specific criteria, 3) print the real estate offers that met specific criteria (independent of whether the offer was accepted or rejected), 4) retrieve printed offers from the printer and deliver them to a file box located on participants' desk, and 5) ensure that the conference room projector light remained on at all times. Each of the tasks was intended to reflect specific EF skills and processes. In addition to evaluating the targeted task behaviors, off-task behaviors were tallied and evaluated for the presence of inattentiveness and perseverative behaviors. See Table 2 for AO tasks and their corresponding EF constructs.

E. Data Analysis

Data were analyzed using SPSS software, version 18. Due to small sample sizes, the data were not normally distributed, necessitating the use of nonparametric analyses. Group differences in performance on AO tasks were evaluated using Mann-Whitney U tests. Spearman's rank order correlations were conducted among the AO tasks and performance on standardized neuropsychological tasks, separately for the MS and the TBI groups.

III. RESULTS

A. Qualitative Evaluation of Feasibility in MS and TBI

Participants with MS and TBI reported to have understood the task instructions, were able to navigate through the virtual environment and maneuver around the virtual obstacles using the mouse, and could complete the tasks in the AO. Qualitative

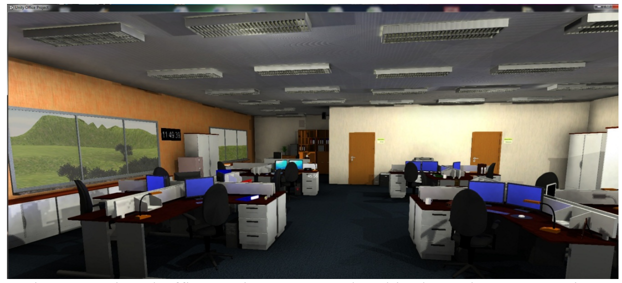

Figure 1. Virtual office environment rendered in the Unity game engine

feedback from participants after completing the VR Office Test revealed that distractors (e.g., phones ringing in the background) made completing the assigned tasks much more challenging. Clinical evaluation of behaviors during AO administration revealed that despite endorsement by the participants that task instructions were fully understood, behaviors suggested superficial comprehension at times. Specifically, it appeared that the criteria for real estate decisions and whether or not to print the real estate offers were too complex, resulting in these tasks depending too heavily on working memory.

B. TBI vs. HC Performance on the AO

Individuals with TBI made significantly fewer correct real estate decisions than HCs, U=4.50, p=.007, r=.69 (For reference, Cohen's conventional effect sizes: small = .10, moderate = .30, large = .50). Individuals with TBI incorrectly printed declined real estate offers significantly less often than HCs, U=5.50; p=.011, r=.68. A trend towards significance was seen in correct delivery of the printed offers to the file box, wherein individuals with TBI were less likely to file offers relative to HCs (U=9.00, p=.053, r=.54). The lack of other significant results may be due to the limited sample size of this pilot study. See Table 3 for a summary of median and range values for TBI and HC groups.

TABLE 2. AO TASKS AND ASSOCIATED NEUROPSYCHOLOGICAL CONSTRUCTS

Assessim Office Task	**EF Construct**
Respond to emails	Selective attention (EF process)
Real estate offer decision task Print real estate offers	Complex problem-solving (EF skill) with working memory component (EF process)
Deliver printed offers to file box	Prospective memory (EF process)
Ensure projector remains on	Divided attention (EF process)

TABLE 3. TBI VS. HC PERFORMANCE ON THE AO

Measures	TBI Median (Range)	HC Median (Range)
Emails correctly replied	4 (1-8)	6 (0-8)
Correct decision, real estate offers	7 (0-9)	12 (5-15)
Declined offers incorrectly printed	0 (0-1)	2 (0-5)
Printed offers delivered to file box	2 (0-4)	4 (0-15)
Projector light missed	3 (0-6)	2 (0-5)
Redundant clicks	0 (0-75)	1 (0-8)

C. MS vs. HC Performance on the AO

Individuals with MS made significantly fewer correct real estate decisions than HCs, *U*=4.00, *p*=0.030, r=.64. Individuals with MS failed to turn the projector light back on significantly more times than HCs, *U*=2.50; *p*=.010, r =.72. The following trends toward significance were also observed: participants with MS correctly responded to fewer emails than HCs (*U*=7.00, *p*=.106*, r=.51);* HCs incorrectly printed declined offers more often than participants with MS (*U*=6.00, *p*=.073, r=.55). Again, the lack of significant results may have been due to the limited sample size. See Table 4 for a summary of median and range values for MS and HC groups.

D. TBI vs. MS Performance on the AO

TBI participants viewed instructions a significantly greater number of times than MS participants (U=5.00, *p*=.048, r=.63). MS participants tended to fail to turn the projector back on more frequently than TBI participants, though not to a significant degree (*U*=7.50, *p*=.106, r=.50). See Table 5 for a summary of group comparisons.

TABLE 4. MS VS. HC PERFORMANCE ON THE AO

Measures	MS Median (Range)	HC Median (Range)
Emails correctly replied	4 (0-5)	6 (0-8)
Correct decision, real estate offers	7 (1-9)	12 (5-15)
Declined offers incorrectly printed	0 (0-2)	2 (0-5)
Printed offers delivered to file box	0 (0-6)	4 (0-15)
Projector light missed	6 (3-6)	2 (0-5)
Redundant clicks	8 (0-28)	1 (0-8)

TABLE 5. TBI VS. MS PERFORMANCE ON THE AO

Measures	*U*	*p*
# times requested to view instructions	5.0	.048*
Emails correctly replied	13.5	.530
Correct decision, real estate offers	14.0	.639
Declined offers incorrectly printed	14.5	.639
Projector light missed	7.5	.106
Redundant clicks	13.0	.530

*p>.05

E. Correlations Among AO and Neuropsychological (NP) Measures in TBI

In the TBI sample, a correlation between the real estate decision task and the NP measure of complex problem solving (WASI Matrix Reasoning) approached significance. Performance on an AO measure of selective attention (responding to emails) correlated significantly with a NP measure of response inhibition and flexibility of thinking (D-KEFS Color Word Test Inhibition/Switching). Printing real estate offers, an AO measure of complex problem solving with a working memory component, correlated significantly with performance on NP measures of cognitive flexibility (D-KEFS Trail Making Test Condition 4 raw score *and* set loss errors). An AO measure of divided attention (turning back on the projector light) also correlated significantly with the NP measures of cognitive flexibility (D-KEFS Trail Making Test Condition 4 raw score *and* set loss errors). See Table 6 for a summary of select correlations.

TABLE 6. CORRELATIONS AMONG AO TASKS AND NEUROPSYCHOLOGICAL MEASURES IN TBI SAMPLE

	ECR	CDRE	DOIP	PODF	PLM
Digit Span Backward	ns	ns	ns	ns	ns
Letter Number Sequencing	ns	ns	ns	ns	ns
D-KEFS Trails 4 raw	ns	ns	**-.889 .044***	ns	**.947 .014***
D-KEFS Trails 4 set loss errors	ns	ns	**-.913 .030***	ns	**.973 .005****
D-KEFS Trails 4 all errors	ns	ns	ns	ns	ns
D-KEFS Color Word Inhibition	ns	ns	ns	**.894 .041***	ns
D-KEFS Color Word Inhibition/Switching	**-.900 .037***	ns	ns	ns	ns
WASI Block Design	ns	-.763 .133	ns	ns	ns
WASI Matrix Reasoning	ns	.821 .089	ns	ns	ns

D-KEFS = Delis-Kaplan Executive Function System; WASI = Wechsler Abbreviated Scale of Intelligence; ECR = Emails correctly replied; CDRE = Correct decision real estate offers; DOIP = Declined (real estate) offers, incorrectly printed; PODF = Printed offers delivered to file box; PLM = Projector light missed; *p<.05, **p<.01

F. Correlations Among AO and NP Variables in MS

In the MS sample, performance on the real estate decision task (AO measure of the complex problem solving) correlated significantly only with a NP measure of complex attention and working memory (WAIS-III Digit Span Backward). In addition, responding to emails correlated significantly with a measure of inhibition and cognitive flexibility (D-KEFS Color Word Inhibition/ Switching). No other significant correlations were found between AO and neuropsychological performance in this sample. See Table 7 for a summary of select correlations.

IV. CONCLUSIONS

The primary aims of this pilot study were to evaluate the feasibility of using a virtual reality-based evaluation tool with TBI and MS populations, to assess the performance of these patient populations relative to HCs, and to explore the relationship between patients' performance on the AO and on standardized EF measures.

The qualitative feasibility evaluation revealed that individuals with MS and TBI were able to tolerate engaging in a virtual environment; they had minimal difficulty maneuvering the virtual environment with a mouse, and they understood instructions for the simpler tasks. However, some of the tasks were decidedly too complex and an unintended consequence of this complexity was too great a demand on the working memory system of participants. Despite the fact that participants were allowed and encouraged to ask to review the decision task criteria at any point during administration, participants often failed to ask for assistance, possibly due to failing to remember that this was an option. Rather, they proceeded throughout the virtual workday either guessing haphazardly at the decision tasks or perseveratively responding in the same fashion to the decision tasks. This approach was evidenced by the fact that both individuals with TBI and MS exhibited significantly fewer errors on the printing decision task; inspection of the raw data revealed that patient populations simply didn't print any of the real estate offers, suggesting that they avoided responding when they weren't sure how to do so correctly. Although this response pattern renders the data uninterpretable, it underscores the capability of virtual tasks to achieve an extremely high level of difficulty, reflecting the complexity of various real-life demands. Ecologically valid tools must be capable of taxing multiple executive processes simultaneously (e.g., increasing stressors and distractions) to be more predictive of real-world performances [9-11]. It appears that the AO is certainly capable of accomplishing this goal. Subsequent iterations of the AO will take this complexity into consideration when determining the appropriateness of difficulty level for target patient populations.

TABLE 7. CORRELATIONS AMONG AO TASKS AND NEUROPSYCHOLOGICAL MEASURES IN MS SAMPLE

	ECR	CDRE	DOIP	PODF	PLM
Digit Span Backward	ns	.872 .054	ns	ns	ns
Letter Number Sequencing	ns	ns	ns	ns	ns
D-KEFS Trails 4 raw	ns	ns	ns	.783 .118	ns
D-KEFS Trails 4 set loss errors	ns	ns	ns	ns	ns
D-KEFS Trails 4 all errors	ns	-.783 .118	ns	ns	ns
D-KEFS Color Word Inhibition	ns	ns	ns	ns	ns
D-KEFS Color Word Inhibition/Switching	ns	ns	ns	ns	ns
WASI Block Design	ns	ns	ns	.783 .118	ns
WASI Matrix Reasoning	ns	ns	ns	**.894** **.041***	ns

D-KEFS = Delis-Kaplan Executive Function System; WASI = Wechsler Abbreviated Scale of Intelligence; ECR = Emails correctly replied; CDRE = Correct decision real estate offers; DOIP = Declined (real estate) offers, incorrectly printed; PODF = Printed offers delivered to file box; PLM = Projector light missed; *p<.05

Quantitative evaluation of the data revealed that the AO was able to successfully distinguish TBI subjects from HCs on measures of selective and divided attention, problem solving, and prospective memory. Specifically, individuals with TBI performed overall more poorly on all the tasks in the AO in comparison to HCs. Although these results weren't always supported by statistically significant p-values, effect sizes were often large, suggesting that failure to reach significance was more likely a product of small sample size than the lack of an effect. The only variable that failed to provide useful clinical information was the printing decision task, which was rendered uninterpretable as described above. Impaired performance on the tasks within the AO is consistent with deficits documented on standardized neuropsychological measures [7, 32-36].

Quantitative evaluation of the MS data revealed that the AO successfully differentiated the MS participants' performance from that of HCs on all of the targeted EF constructs, with the exception of the printing decision task. Such findings were supported by statistically significant results on two tasks, paired with a trend toward significance on two other measures. Again, the only exception was the uninterpretable printing decision task. Impairments in problem solving and selective and divided attention, as evidenced on the AO, are functions reported in the literature to be compromised in MS [37, 38].

Comparison of patient groups on AO tasks was conducted to explore the differential sensitivity in the TBI and MS populations. Participants with TBI requested to review the real estate criteria instructions more frequently than participants with MS. The MS group had a slightly greater tendency to miss turning the projector back on relative to the TBI group. Other than these findings, the two clinical groups were similarly impaired on AO tasks. A differential sensitivity analysis with a larger subject sample may provide richer information regarding distinct patterns of performance between different patient groups.

Exploration of the relationship between performance on AO tasks and standardized neuropsychological EF tasks was conducted for each patient group separately. For participants with TBI, each AO task showed a signficant relationship or trend toward significance with one to two neuropsychological measures. In contrast, for participants with MS, significant findings or trends toward significance were seen between only two AO tasks (correct decision on real estate offers, printed offers delivered to the file box) and standardized NP measures. D-KEFS Trails 4 raw score was the standardized test that was most frequently associated with AO tasks, whereas Letter Number Sequencing was the only standardized test to not relate strongly to any AO measure. In general, there were striking patterns that arose between AO and standardized measures, but given the large number of correlations that were performed, it is unclear whether the significant findings and other trends toward significance observed were due to chance. Given the small sample sizes, it is difficult to draw conclusions in either direction.

The current study demonstrated that the AO was well tolerated by our TBI and MS samples and that performance by the clinical samples on the AO was distinct from that of HCs. Overall, patient performance was poorer than that of HCs across all AO tasks. While these differences were not always supported by significant *p*-values, strong effect sizes suggest that an adequately powered study with greater sample size would demonstrate more robust differences between patient groups and HCs. Evaluation of the relationship between performance on AO tasks and neuropsychological tests of EF revealed that there were more significant relationships demonstrated within the TBI group as compared with the MS group. Given the small sample size, these correlations are inconclusive. However, it should be noted that the rationale for utilizing a virtual reality approach relies on it's ability to mimic real-life, complex, and dynamic situations; given the criticism that paper and pencil tests fail to achieve these characteristics, it is hypothesized that strong and systematic correlations would not necessarily emerge if a larger sample were to be used. Indeed, Renison and colleagues found that their VLT only related to verbal fluency, Zoo Map, and the Modified Six Elements Test [15]. To confirm this hypothesis, we will evaluate these relationships once a larger sample has been collected.

One limitation of the current study is that we were unable to evaluate the ecological validity of the AO by comparing performance on AO tasks to self-report of EF impairments in daily life [e.g., Dysexecutive Questionnaire (DEX); Frontal Systems Behavior Scale (FrSBe)] or performance on functional instruments [e.g., the Multiple Errands Test (MET); Executive Functions Performance Test (EFPT)] [5, 39-41]; these tests were not included in the currrent testing battery. Given that these self-report measures and functional instruments have been reported to relate to performance on the VAP-S, the VMall, and the VLT [15, 21, 26], evaluating for the presence of such a relationship with AO tasks would be an important next step.

Deficits in executive function have been shown to contribute to obstacles in community integration and return to employment, which in turn negatively impact quality of life. Therefore, continued development of the AO is expected to lead to improved ability to evaluate EF skills and processes not currently captured by existing virtual environment evaluation tools.

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