Research Article

The Development of A Psychomotor Vigilance Test Battery and the Assessment of Vigilance Change in Reaction to Mental Work Load

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Summary

This study aims to establish a battery for assessing vigilance by bringing together tests assessing various cognitive functions and to evaluate vigilance change in reaction to cognitive workload.

Vigilance, generally defined as sustained attention and the ability to remain alert and responsive to external stimuli, is claimed to be indicative of alertness on the sleep wake spectrum regardless of any cognitive or behavioral response.

The study comprises 102 participants (18-54 years of age). The study group of 51 participants (31 female) took the Psychomotor Vigilance Test (PVT) followed by tests assessing various cognitive functions and then retook the PVT. These computerized tests lasted 60 minutes. The control group of 51 participants (33 female) retook the PVT following a 40 minute resting period.

Mean reaction time (RT) on the initial PVT was 292.45±32.5 ms. A significant increase in RT was found when measures on the initial and final PVT were compared in the study group (p<0.01). This difference, which was absent in the control group, was concluded to reflect a decrement in vigilance due to cognitive workload.

The results in this study were consistent with the cognitive resource theory of vigilance decrement and imply that there was an increase in the RT following the administration of various cognitive tests that cause cognitive workload.

Key words: Cognitive workload, Attention, Reaction time

Psikomotor Vijilans Test Bataryası Geliştirme ve Bilişsel İş Yüküne Bağlı Vijilans Değişimlerinin Değerlendirilmesi

Özet

Çalışmada, çeşitli bilişsel işlevlerin ölçülmelerinde kullanılan testlerin bir araya getirilmesi ile vijilansın ölçülmemesini sağlayabilecek bir bataryanın geliştirilmesi ve bilişsel iş yüküne bağlı vijilans değişimlerinin değerlendirilmesi amaçlanmıştır.

Dikkatin sürdürülebilmesi, çevresel uyarıları fark etme ve uygun yanıt verebilmek yetisi olarak tanımlanabilen vijilansın, bilinçlen veya davranışı bir tepkiden söz etmeksizin, uyku-uyanıklik ekson üzerinde, uyankılık düzeyini işaret ettiği savunulmaktadır.


İlk uygulanan PVT'de tepki sürelerinin ortalaması 292,45±32,5 ms bulunmuştur. PVT ve bilişsel test sonuçları literatürle uyumlu olup, çalışma grubunda PVT sonuçları çalışmanın başında ve sonunda değerlendirildiğinde teki sürelerinde anlamlı bir fark gözlenmiştir.
(p<0.01). Kontrol grubunda gözlenmeyen bu farklı bilişsel iş yüküne bağlı vijilans kayına işaret etmekte olduğu düşünülmektedir. Bu çalışma, bilişsel iş yüküne bağlı kaynak teorisi ile uyumlu olup, çeşitli bilişsel testlerin uygulanmasının ardından artan tepki süresinin bilişsel iş yüküyle ilişkisini işaret etmektedir.

Anahtar Kelimeler: Bilişsel iş yükü, Dikkat, Tepki süresi

INTRODUCTION

Individuals experience different levels of sleepiness and wakefulness from the moment they wake up until their bedtime. Throughout the day we need a particular level of wakefulness in order to execute simple life-sustaining activities. For example; the level of wakefulness required for driving is definitely different from the level while resting. This state called vigilance has received various definitions in recent studies and its importance has been emphasized. While animal scientists define vigilance as “to be alert to signs of danger”, psychiatric clinicians define it as “wakefulness, alertness, and sustained attention”(20). Vigilance was first defined in 1920's by a famous neurologist Henry Head(13) as “state of high grade physiological efficiency necessary for effective action both conscious and reflex, which depends on the structure and condition of the nervous system”. Mackworth, who had been conducting studies on the measure of vigilance since 1940's, defined vigilance as a state of “readiness” to detect and react to infrequent, or randomly occurring and hardly distinguishable variations. He also noted that distinct from attention, this experience does not depend on the consciousness state(18).

Although vigilance may be considered as a level of cognitive functioning, from a neuropsychological perspective, vigilance indicates a wakefulness state on the sleep-wake spectrum, regardless of conscious or unconscious responses(20). This is important because, functional responsiveness of the central nervous system to external stimuli, even in the absence of a conscious response, should not be ignored. Just like in wakefulness, brain responses to external stimuli can be observed during different conscious states such as sleep and anesthesia(21).

Vigilance is necessary for executive functions(20). Therefore, it is crucial in professions requiring a certain level of cognitive capacity and sustainable attention. Vigilance decrement (VD) is defined as the diminished capacity of being vigilant and being unable to sustain attention(22). There are many studies drawing attention to the fact that traffic and occupational accidents due to diminished vigilance level create a major problem(3). Thus the ability to measure VD and to determine the possible factors leading to it has vital importance. Many factors such as fatigue, sleep deprivation, central nervous system diseases, alcohol, the use of certain foods and drugs were reported to cause VD(4,17,18,28). These factors may be related to task (i.e. duration of task, signal specifications), current cognitive or physical condition of the person (i.e. motivation, fatigue and insomnia, age and disease), or environmental conditions. VD can be evaluated by measuring changes of vigilance level in various conditions and occasions. VD can be inferred from the decrease in correct response rates in the detection of critical signals which need to be perceived and responded to(22). It can also be observed from the increase in RT over time while responding to these detected signals(29).

Broadbent (1971) hypothesized that the need for attentional mechanisms originates from the limited capacity of the brain for processing information(1). According to cognitive resource theory of VD, vigilance depends on the cognitive capacity related
to the task. VD arises from the consumption of cognitive resources for sustaining attention faster than their rate of replacement\(^{(2,7,25)}\). A task's cognitive workload is defined as the relationship between brain's own resources and the detected amount of cognitive capacity required for that task\(^{(12)}\). In other words, a cognitive workload reflects the amount of cognitive processing carried out during fulfilling task requirements\(^{(5,9,28)}\). The increase in cognitive workload is accompanied by a decrement of vigilance over time\(^{(28)}\).

Since the 1940's there has been an increase in the number of studies focusing on vigilance. The increase in number of professions which require tracking and detecting infrequent events and signals, especially while working with machines and vehicles, may account for the escalation in research activities on vigilance\(^{(18)}\).

Vigilance may be inferred from RT measures acquired during the implementation of psychomotor vigilance tests\(^{(29)}\) or from behavioral measurements of performance on cognitive tasks that require sustained attention\(^{(20,29)}\). Physiological methods, providing objective data on brain responsiveness, which may or may not be evaluated together with behavioral data, may be advantageous due to their time and spatial resolution. However, these methods can be expensive and also minimally invasive or impracticable in some situations. Therefore psychometric measurements providing behavioral data are still frequently employed methods for clinical, human resources and educational research purposes due to their affordability and convenience.

This study aims to establish a battery for evaluating vigilance by bringing together tests used to assess various cognitive functions and to measure changes in vigilance in reaction to cognitive workload on tasks which require sustained and focused attention. While applying the cognitive workload, VD is expected to be evaluated from changes in RTs and rates of correct and incorrect (late) responses, as measured by the psychomotor vigilance test (PVT).

**MATERIAL AND METHODS**

In this study, 106 healthy participants were recruited for the protocols. On the day of the study, participants were obliged to refrain from the consumption of alcohol, coffee, or any other drugs/medication which may have an effect on visual motor coordination and performance on cognitive tasks. Participants who had psychiatric or chronic health problems and/or lack of sleep on the previous night were excluded from the study. Additionally, the data obtained from participants who were not able to complete the tasks till the end of protocol were excluded from the analysis. Consequently, appropriate data from 102 participants (ages 18-54, mean age: 24.9 SD: 7.9 years) were evaluated.

Before starting the experiment protocol, each participant signed an informed consent form and filled in some psychometric questionnaires (Personal information form, SCL-90 R Symptom Screening Test, Epworth Sleepiness Scale, Anxiety Scale and Edinburgh Handedness Test) regarding psychological and demographic information.

The participants were randomly divided into two groups; study and control. The study group performed a 10-minute PVT followed by some cognitive tasks assessing various executive functions related to certain components of vigilance. At the end of this procedure the participants retook the same PVT which was initially presented. Duration of whole protocol was around 60 minutes per participant. The control group also performed the initial 10-minute PVT but were then asked to have a 40 minute break under the supervision of the experimenter. During this period, participants were allowed to have light snacks, but not allowed to sleep or to engage in any activity that may affect them.
physically or mentally neither were they allowed consuming any beverages such as tea, coffee or coke. Finally, another 10-minute PVT was administered to the participants.

All applied tests, which evaluate cognitive and executive functions related to certain components of vigilance and sustained attention, are parts of the Psychology Experiment Building Language (PEBL) library. Applications and scopes of each of the cognitive tests given to the participants in counterbalanced order are presented below.

**COMPUTERIZED COGNITIVE TESTS**

**Wilkinson and Haughton Psychomotor Vigilance Tests (PVT):** The participants were required to respond by pressing the space bar as soon as they perceived a visual stimulus, which appeared on the screen at randomized interstimulus intervals (ISI) within a range of 2000-12000 ms. The visual stimulus used in this study was a red circle, 2 cm in diameter. The test normally takes around 10 minutes and measures psychomotor vigilance, wakefulness, continuous and sustained attention and simple RT\(^{(29)}\). The participant's simple RT and response accuracy were evaluated.

**Conner Continuous Performance Test (CPT):** The participants were asked to press the space bar as soon as letters of the alphabet randomly appeared on the screen at preset intervals, except for the letter X, in which case the participant needed to inhibit response. The letters were 1.5x2cm in size and ISI were preset at 1000, 2000 or 4000 ms. The test normally takes around 14 minutes and measures psychomotor vigilance, selective and sustained attention, response inhibition and recognition RT\(^{(5)}\). The participant's recognition RT, response accuracy and commission error rates were evaluated.

**Simon Test:** The participants were required to press the left button on the keyboard when the red circle appeared; and the right button when the blue circle appeared on the screen. The participants were asked to ignore the location of the stimuli which appeared on the left right or center of the screen. The circles were 4.5 cm in diameter and appeared on the coordinates (vertical pixel, horizontal pixel); (0.0) (middle), (0, -200), (0, -100), (0, -50) (0 50) (0,100) (0,200). The test normally takes approximately 5-6 minutes and measures choice RT, selective attention, response inhibition and resistance to interference factor. RT to congruent and non-congruent stimuli and the rate of correct responses were evaluated\(^{(26)}\).

**Corsi Block Test:** The test consisted of nine blue squares with a dimension of 4x4cm. The participants were asked to recall the sequence and location of squares which successively lighted up and to specify them in the same order. The number of flashing squares progressively increased as the participant recalled them correctly. The administration of the test normally takes approximately 3-4 minutes and measures short term visual spatial working memory\(^{(16)}\). The participant's Total Score was calculated as the product of the number of correct trials and maximum length of correctly recalled trials (the block span score).

**Timewall Test:** This is a visual spatial perception task in which a 0.5 cm sized green square moves downward from the top of the screen at a constant velocity and disappears behind a red wall covering 1/3 of the screen. The participants were required to predict the exact time the green square reaches the bottom of the screen and press the space bar at that estimated time\(^{(10)}\).

**Change Detection Test:** This test is an extension of the change blindness paradigm. The participants were required to detect changes in the stimuli on the screen which consisted of circles in various sizes and colors. These changes were either
in color, size, or location of one of the circles in the display. After detecting the change in the stimuli, the participants had to freeze the screen by pressing the space bar and mark the change by clicking on its location (24).

The participants were seated on a comfortable chair 50 – 60 cm from the screen with an effective viewing area of 337.9 mm x 270.3 mm. Temperature of the recording room was measured as 22.9°C on average. As Jensen and Munro (1979) described in their protocol, the participants were asked to keep their fingers on the keys and were advised to use their dominant hand.

**Statistical Analysis:** Descriptive Statistics of the data is presented as mean and standard deviation for continuous variables and frequency and percentile for categorical variables. The t-test for continuous variables and Chi-squared test for categorical variables were performed for comparisons between the study and control groups. Pearson Correlation test was employed to measure the association between continuous variables. P value was set 0.05 for statistical significance.

**RESULTS**

Demographic information and sleep durations of the participants the night before the protocol are presented in Table 1. There was no statistically significant difference among the groups in regard to these variables. The mean of RTs of all participants (regardless of their group) for the first PVT was 292.45±32.5 ms (with a range of 231.01 and 388.71 ms). Number of late responses, comprised of RTs exceeding 500ms, was observed to be 1.3±1.8 on average (with a range of 0 and 8). Number of commission errors, which occur by pressing the bar before the stimulus appeared, was on average 1.5±2.2 (with a range of 0 and 17). There was no statistically significant difference between the study and control groups in respect to mean of RTs, number of correct and incorrect responses on the first PVT test. These results are shown in Table 1.

| Table 1: Demographic Data and First PVT Session Measures (M: Male, F: Female) |
|---------------------------------------------|-------------------------------|------------------|
| All Participants | Study Group | Control Group |
| Age | 24.9±7.9 | 24.7±7.5 | 25.0±8.3 |
| Gender | 38 M, 64 F | 20 M, 31 F | 18 M, 33 F |
| Sleep Duration in Previous Night | 6.9±1.4 | 6.8±1.5 | 7.0±1.4 |
| Mean RT (ms) | 292.45±32.5 | 297.69±34.6 | 287.20±29.8 |
| Number of Correct Responses | 71.8±3.4 | 71.2±3.3 | 72.3±3.4 |
| Number of Late Responses | 1.3±1.9 | 1.3±1.9 | 1.3±1.8 |
| Number of Commission Errors | 1.5±2.2 | 1.5±2.7 | 1.5±1.6 |
Results Regarding the Evaluation of Changes in Vigilance

In the study group, mean RTs (317.96±45.56 ms) obtained during the PVT administered after the cognitive tasks was significantly higher than mean RTs (297.69±34.56 ms) obtained during PVT taken before cognitive tasks (p < 0.001, see Figure 1). Additionally, the number of late responses given in the last PVT (2.5±3.6) was significantly higher than those (1.3±1.9) in the first PVT (p<0.05, see Figure 2). Whereas in the control group, there was no statistically significant difference between the two PVT sessions in respect to mean RT and the number of correct and late responses.

In the study group, although there was a decrease in the number of correct responses in the last PVT session compared to the first one, there was no statistically significant difference between two PVT sessions. However, there was a statistically significant negative correlation between differences in the mean RTs (last PVT RT-first PVT RT) of two PVT sessions and number of correct responses given in the last session (r=-0.52; p<0.001), and there was a statistically significant positive correlation between differences in the mean RTs (last PVT RT-first PVT RT) of two PVT sessions and number of late responses in the last session (r=0.59; p<0.001). In other words, the greater the increase in RTs on the last PVT, the greater was the increase in the number of late responses on the last PVT.

There was no such significant relationship between the difference of RTs (of the first and last PVT session) and any of the variables in the first PVT session. Bell curve of frequency distributions of PVT are shown in Figures 3.

On the other hand in the study group, there was significant positive correlation between the number of correct responses for non-target stimuli in the CCPT and the difference between mean RTs in the two PVT sessions (r=0.33; p<0.05). Bell curve of frequency distributions of CCPT are shown in Figures 4.

According to these correlations, as the participants tend to give correct responses to non-target stimuli in CCPT, the differences in RTs between the first and the last PVTs implying VD, increased. The differences in RTs between the two PVT's was found to have a negative correlation with the ratio of the number of correct responses RT in CCPT (Rho=-0.32, p < 0.05).

The participants in the first quartile and the last quartile in regard to the difference in RTs of the first and the last PVTs were compared in respect to the ratio of number of correct response/RT in the CCPT. This ratio (1.06±0.12) was statistically higher (p<0.05) in individuals who had relatively lower prolonged RTs, implying lower VD, than for individuals (0.94 ± 0.08) who had relatively higher prolonged RTs implying higher VD.
Figure 1: Comparison of mean RTs for the first and last sessions of PVT in the Control and the Study groups.

Figure 2: Comparison of late response numbers for the first and last sessions of PVT in the Control and the Study groups.
Figure 3: Bell curve frequency distributions of differences in mean RT in the first and last sessions of PVT in the Study group.

Figure 4: Bell curve frequency distributions of correct response numbers for non-target stimuli in CCPT.
DISCUSSION

In related literature, there are three common measurement methods which need to be taken into account for evaluating changes occurring in vigilance in accordance with the cognitive resources theory. The first method covers the behavioral measurements such as RT and response accuracy rates usually obtained from psychomotor vigilance tests. The second one involves the evaluation of brain responsiveness and the brain's use of cognitive resources, which can be interpreted by evaluating objective data derived from electrophysiological and neuropsychological measures. The last method makes use of stress and task workload indexes as indicators of the individual's degree of task engagement\(^{25,28}\). As a measurement method, this study employed behavioral data obtained by PVT. The changes in RT and accuracy rate of responses are some behavioral variables that can be used in assessing vigilance decrement. The results in this study were consistent with the cognitive resource theory of vigilance decrement and imply that there was an increase in the RT following the administration of various cognitive tests that cause a cognitive workload. The significant differences in RT and number of late response measurements taken prior to and after the administration of cognitive tests assessing the focus of attention and it's sustainability, was thought to be related with VD associated with cognitive workload in the study group.

There were statistically significant correlations between the differences in mean RT (last PVT RT - first PVT RT) and the number of correct and late responses in the last session. These correlations indicate that as RT differences increased between the first session and last session, there was also an increase in the number of late responses and decrease in correct responses. These differences between RTs were not correlated to the variables in the first session of PVT. This indicates that VD was related with the administration of cognitive tests and cognitive workload rather than situational and individual factors such as the participant's motivation. These associations have not been observed in the control group.

In this study, RT differences, between the first and last sessions of PVT, indicating vigilance decrement, were correlated with cognitive performance parameters which were related with certain executive functions such as number of correct responses, number of late responses and the ability of response inhibition to non-target stimuli. While assessing vigilance through behavioral variables, it has been emphasized that many components related with person's performance should be evaluated together. Sustained attention, speed and ability to respond to stimuli were the major components in question.

During the administration of increasingly challenging tests used to evaluate vigilance through measuring simple, recognition and choice RTs, other variables such as correct response rates as well as lack of inhibition were also evaluated\(^{5}\). Likewise, in the evaluation of the cognitive competence of individuals working under intensive cognitive or physical workload, appropriate responsiveness is as important as response speed. It is arguable which are more effective when comparing individuals' with late but correct responses to individuals' who respond more rapidly but erroneously in respect to cognitive competencies and vigilance levels. One is more speed-oriented and has a risky response style while the other one reflects a more cautious approach. Ideally, it is aimed to have a balanced response style as a reflection of accepted standards which is rapid with a minimal error rate.

There was a statistically significant positive correlation between the differences
in RT (RT on the last PVT minus RT on the first PVT) that measures vigilance decrement and correct number of responses in CPT, which evaluates selective attention and ability of inhibition. Based on this correlation, in our study group, there were cautious participants responding correctly with prolonged RT. As a result, it can be concluded that in CPT dividing the number of correct answers by RT can reflect both a faster and less error-response style. This ratio is inversely proportional with the RT difference between the first and last PVT indicating vigilance decrement.

These results imply that while measuring vigilance, it is more important to evaluate the ratio of the number of correct answers with RTs instead of evaluating the number of correct responses and RTs separately. A bell curve generated from cognitive test results administered in standard setting and reflecting a frequency distribution can be used in the evaluation of competence of employees under intensive cognitive workload or in the election of candidates to work on tasks requiring the use of these executive functions.

In this case, the person's raw score will be converted into standard scores in order to determine which percentile it corresponds to in the bell curve reflecting the person's rank in the population. The use of bell curve created from test results conducted under standard conditions within samples from a certain profession, educational level or in patient groups, instead of a heterogeneous population, will minimize ceiling or floor effects. It may then be possible to use vigilance batteries created for specific purposes such as determining pilot candidates.

In groups where the evaluation of vigilance and cognitive workload are required, psychomotor vigilance battery may be aimed to be created by bringing together tests that evaluate planned executive functions in accordance with the requirements of the situation and the characteristics of the group by manipulating variables such as degrees of difficulty, duration, stimulus frequency.

It is possible to calculate behavioral vigilance scores by converting raw scores obtained from these cognitive tests administered in the standard conditions into standard scores. Vigilance plays an important part in medical environments where brain functions and the course of neurodegenerative diseases are evaluated, as well as in work environments, involving healthy subjects working on tasks requiring attention, and in the field of education where memory, attention and learning play an important role.

Also, there are some tests developed with the aim of assessing attention and competence level of pilots and drivers used in our country; however there are not enough studies to prove their competence in measuring vigilance and their suitability for use in the Turkish population.

The results of this pilot study, designed to determine the changes in vigilance with the use of the psychomotor vigilance test, are consistent with studies examining vigilance with behavioral data based on RT and response accuracy. Based on the results of this pilot study, the establishment of a battery suitable for assessing changes in vigilance for use in the Turkish population is aimed.

The investigation of vigilance in certain neurodegenerative diseases, sensory impairments and certain mental illnesses such as depression and the use of the battery in the medical field for early diagnosis of several diseases which may affect vigilance may be possible. With this goal achieved, vigilance and vigilance changes may be objectively measured. Thus the establishment of such a link connecting behavioral data, associated with some elements of vigilance, supported with objective data of brain responsiveness will enable the evaluation of vigilance in different states of consciousness such as sleep and wakefulness regardless of the presence of a cognitive or behavioral...
response or the use of executive functions. This establishment could be useful in the assessment of sleep deprivation, cognitive performance, and competency in healthy individuals working on night shifts as well as in the monitoring of the course of neurodegenerative diseases.

It has been highlighted that desynchronization in the circadian rhythm and sleep–wake cycle in night shift workers or people with sleep disorders may in time lead to vigilance decrements with measurable neurobehavioral consequences. Indeed there are many studies reporting errors and work accidents due to detected vigilance decrement in night shift workers and professionals working in medical environments. An integrated approach, evaluating behavioral data with objective measurements, developed for measuring vigilance may be used to evaluate psychovigilance in occupations entailing intensive cognitive workload and which require the implementation of executive functions such as planning, focus of attention, sustained attention and decision-making. Long-distance drivers, military and civilian pilots, security guards working on night shift, doctors and nurses, brokers in the stock market and foreign affairs negotiators are some examples for these professions and businesses. People working at jobs that require sustained attention and quick decision making, planning and acting, may be subject to vigilance decrement due to intense pressure and stress. In tasks that require the sustained attention, vigilance can be affected by the difficulty and the nature of the task, the cognitive requirements of the task as well as psychological factors such as motivation, anxiety, impulse control, and stress, physiological factors such as sleep deprivation, fatigue, substance use that affects central nervous system, and environmental factors such as temperature and noise.

This integrated approach for the objective evaluation of the vigilance, can determine many factors that mediate, reduce or multiply the severity and duration of these effects. Thus it will be possible to obtain information on tolerance to sleep deprivation and physical, psychological and environmental factors which may have negative impact on vigilance in people working in professions which may be affected by vigilance decrement. For example it will be possible to obtain information about ideal work periods, tolerance to sleep deprivation in individuals working in professions which involve intense stress such as military and civilian pilots, night shift workers and long-distance drivers. Also vigilance decrements due to disturbances in circadian rhythm and "jet lag" symptoms resulting from time differences in long distance travelling can be assessed with this integrated approach. Also the efficiency of methods used to eliminate jetlag symptoms can be assessed by evaluating vigilance, hence various methods for compensating for or eliminating vigilance decrement can be developed for night shift workers, long distance passengers and people affected from stress and diseases.

In addition to its use in the professional work field, this developed integrative method can become an important tool in the field of education for evaluation and investigation of factors affecting memory, learning process, and cognitive activities related to vigilance.

**CONCLUSION**

The results are consistent with the cognitive resource theory of vigilance decrement and suggest that there is an increase in RT following the administration of various cognitive tests that cause cognitive workload. The significant differences in RT and number of late responses prior to and after the
administration of cognitive tests assessing focus of attention and its sustainability are thought to be related with vigilance decrement associated with cognitive workload. This study has made use of the development of a battery enabling the assessment of vigilance change in reaction to cognitive workload. It is possible to bring together various tests for evaluating different executive functions and to develop various batteries in order to evaluate vigilance changes in different professional and patient groups as well as working conditions. Finally there are many neural networks and functional systems affecting alertness and attentional systems which are directly related with vigilance. Because of these multiple structures and effects of neural systems it is impossible to discuss vigilance and related concepts on a single dimension\(^2,20\). Therefore, it is crucial to evaluate vigilance within a multi-dimensional analysis, together with a number of physiological and behavioral measurements and control for as many experimental parameters as possible.

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