Effects of water temperature and dissolved oxygen on daily feed consumption, feed utilization and growth of channel catfish (*Ictalurus punctatus*)

J. Alejandro Buentello, Delbert M. Gatlin III *, William H. Neill

Department of Wildlife and Fisheries Sciences, Texas A&M University System, College Station, TX 77843-2258 USA

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Abstract

Feed intake (FI), feed efficiency (FE), protein efficiency ratio (PER) and weight gain (WG) of juvenile channel catfish initially weighing 15.0 ± 0.23 g (10–12 cm initial total length) were evaluated under three regimes of time-varying water temperature (mean daily water temperature for Stoneville, MS, USA; mean +3; and, mean −3°C) and three of dissolved oxygen (DO; 100, 70 and 30% air saturation, at each temperature), Two independent experiments lasting 6 and 8 weeks, respectively, simulated spring and fall temperature and photoperiod patterns. Temperature–oxygen regimes were applied to randomly assigned duplicate 110-l aquaria with individual biofilters. Fish were fed once daily, to slight excess, a commercial catfish floating feed. After 45 min, uneaten feed was collected, dried and weighed; then FI was calculated by difference. Fish in each aquarium were weighed collectively, biweekly. In both experiments higher temperatures and higher DO levels produced increased feed consumption. A multivariate regression model was fitted to the data to describe the combined effects of temperature and DO on FI. There was a progressive reduction in FI as DO declined from 100 to 30% air saturation. In both trials weight gain was higher for fish held 3°C above the mean water temperature at 100% air saturation values of DO; whereas, the lowest values of WG were obtained for fish held at 30% air saturation and 3°C below the mean water temperature. Weight gain increased with temperature, with maximum rates reached at 27.1°C with DO equivalent to 100% air saturation. In contrast, when DO was 30% air saturation, growth rates plateaued as ambient temperature exceeded 22.8°C. This model will assist in optimization of feeding practices in channel catfish aquaculture. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Water temperature; Dissolved oxygen; Feed consumption; Channel catfish

* Corresponding author. Tel.: +1-409-847-9333; fax: +1-409-845-4096; E-mail: d-gatlin@tamu.edu

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1. Introduction

Water temperature, dissolved oxygen concentration (DO), and photoperiod are potent influences on feed consumption, metabolic rate and energy expenditure, and thus, on growth of poikilothermic vertebrates, including fish (Brett, 1979; Elliott, 1982; Dutta, 1994; Bhikajee and Gobin, 1998). Therefore, the effects of these environmental factors on fish growth and metabolism warrant thorough investigation.

Feeding is the single largest cost in raising channel catfish, often exceeding 50% of the operating expense (Giachelli et al., 1982). For aquaculture to be profitable it is important that the cultured organism’s rates of feed intake and growth be both high and uniform (Brett, 1979; Elliott, 1982; Koskela et al., 1997). In practice, however, environmental conditions such as temperature, salinity, light and DO are often difficult to control; so, they may be only monitored or maintained at tolerable, as opposed to optimum, levels (Burel et al., 1996).

The present study was designed to investigate the effects of seasonally changing DO, temperature and their interaction, on feed consumption and weight gain of juvenile channel catfish. Attempts were made to estimate optimal temperature-DO combinations for feed consumption, feed conversion efficiency and growth.

2. Materials and methods

Feed intake (FI), feed efficiency (FE), protein efficiency ratio (PER) and weight gain (WG) of juvenile channel catfish (*Ictalurus punctatus*) were evaluated under three water temperature regimes typical of the southeastern United States where a majority of the channel catfish production occurs (mean daily water temperature for Stoneville, Mississippi, USA; mean +3; and, mean −3°C) and three of DO (100, 70 and 30% air saturation, at each temperature). In two independent feeding trials, photoperiod and mean temperature combinations were designed to mimic spring and fall patterns occurring at 34.2° N and 92° longitude (Fig. 1). Spring and fall trials were carried out over 6 and 8 weeks, respectively.

![Fig. 1. (A) Patterns of water temperature during spring and fall experiments; (B) Photoperiod profiles for Stoneville, Mississippi, USA, that were simulated in the experiment.](image-url)
Juvenile channel catfish with an initial weight of 15.0 ± 0.23 g (mean ± S.D.; 10–12 cm initial total length) were obtained from ponds at the Aquacultural Research and Teaching Facility of the Texas A&M University System (Burleson, TX). One hundred and eighty fish in each trial were randomly allocated to the nine temperature-DO treatments, with two replicates per treatment. Each group of 10 fish was placed in a 110-l glass aquarium containing aerated and recirculated well water. Temperature–oxygen regimes were applied to randomly assigned aquaria equipped with individual biofilters. Water temperature was maintained at nominal values ±1°C by opposing room air refrigeration with thermostatically controlled heaters in the individual aquaria. Compressed air, pure oxygen and/or pure nitrogen were used to maintain DO (within 5% accuracy) at the three treatment levels. Temperature and DO were measured once daily in each aquarium for maintenance of selected treatment levels. Individual aquaria were sampled constantly (one aquarium each day) for temperature and DO, to evaluate differences in oxygen consumption of fish in the post-prandial state. All measurements of water temperature and DO were performed via a YSI 610 multi-parameter environmental monitoring system. Weekly measurements of water quality were carried out for pH, ammonia, nitrite and nitrate levels and were kept within suitable levels for channel catfish Lee, 1991. Water in all aquaria was completely replaced with fresh wellwater every 2 weeks. Fish were acclimatized to experimental conditions for 2 weeks prior to initiation of each feeding trial.

Fish were fed once daily (0830) an excess ration of a commercial catfish floating diet containing 40% crude protein (Rangen, Angelton, TX). After 45 min, uneaten feed was collected, dried and weighed; then FI was estimated by difference. Fish in each tank were collectively weighed biweekly.

Established formulas (Halver, 1989) were used to compute and express FI, FE, PER and WG of juvenile channel catfish. All statistical analyses were conducted using the Statistical Analysis System (SAS Institute, 1996). Possible differences among treatments were tested using a nested ANOVA model for FI, WG, FE and PER. A P value of less than 0.05 was taken to indicate statistical significance.

3. Results and discussion

Survival of fish was 100% in both trials. The FI of fish was influenced both by water temperature and DO in both trials (Fig. 2). As the temperature increased from 15.7 to 31.7°C, FI also increased. Due to limitations of the experimental system, we were not able to produce a descending limb (supra-optimal temperature) on the rate-temperature curve for feed consumption. Feed intake was significantly lower at 15.7°C than at all other temperatures, and FI during the spring experiment was higher at 30°C and 100% air saturation than at any other combination in either experiment. There was a progressive reduction in FI as DO declined from 100 to 30% saturation.

Growth patterns for juvenile channel catfish in terms of WG increment for both the spring and fall feeding trials are shown in Fig. 3. In both trials WG was greatest for fish held 3°C above the mean water temperature at 100% air saturation values of DO; whereas, lowest values were obtained for fish held at 30% air saturation and 3°C below the central water temperature. Weight gain increased with temperature, with maximum
Fig. 2. Feed intake of channel catfish (g/100 g body weight (BW)/day) obtained for both spring (A) and fall (B) experiments. Each data point represents the mean of two replicates for each temperature/oxygen combination averaged over the duration of each trial.

rates (averaged for both trials) reached at 27.1°C and 100% air saturation. In contrast, WG almost plateaued as ambient temperature exceeded 22.8°C when DO was 30% air saturation. Marked differences in WG were observed at each level of DO (Fig. 4) and temperature (Fig. 5). In both experiments of the present study, apparent FE ranged from 0.1 to 1.0 (g gain/g fed), and showed significant differences related to temperature and oxygen levels (Fig. 6). The ranges of PER were temperature/oxygen-dependent as well.

The association between WG, water temperature and DO for channel catfish found in this study (and disregarding transient-state effects) is described by Eq. (1):

\[
WG = 3.061 - 0.099(T) - 0.0663(O) + 0.004258317(T \times O)
\]

where: WG = Weight gain (g), \(T\) = Water temperature (°C), \(O\) = Dissolved oxygen (% air saturation).

Fig. 3. Total weight gain increment (expressed as percent of initial weight) for juvenile channel catfish (10 fish/aquarium; two replicates per treatment) during spring (A) and fall (B) experiments. Symbols with different superscript letters indicate intergroup statistical differences (\(P < 0.05\)) among treatments at the end of week 6. Mean indicates mean daily water temperature for Stoneville, Mississippi, USA, with +3 and −3 indicating 3°C above and below the mean temperature, respectively. Dissolved oxygen concentration is noted as 100, 70 or 30% air saturation.
Fig. 4. Dissolved oxygen effects on weight gain increment (percent of initial weight) for channel catfish (10 fish/aquarium; two replicates per treatment) averaged for both spring and fall experiments (each at 6-weeks duration). Superscript letters express intergroup statistical differences between percent air saturation levels of dissolved oxygen. Means not sharing a common letter are significantly different from each other ($P < 0.05$).

Fig. 5. Temperature effects on weight gain increment (percent of initial weight) for channel catfish (10 fish/aquarium; two replicates per treatment) averaged for both fall and spring experiments (each at 6-weeks duration). Superscript letters express intergroup statistical differences among temperature regimes. Means not sharing a common letter are significantly different from each other ($P < 0.05$). Mean indicates mean daily water temperature for Stoneville, Mississippi, USA, with +3 and −3 indicating 3°C above and below the mean temperature, respectively.
To better examine data from the present study, an XYZ coordinate system was used to locate the response Z in a tridimensional (3D) scatter plot. Interaction tests (SAS Institute, 1996) were used to evaluate statistical significance of individual factors and interactions among them. Then, selected factors (temperature, oxygen and temperature * oxygen) were submitted to a general linear model procedure (SAS Institute, 1996) to obtain numerical coefficients for the predictive equation. This model generated new data points through the use of the inverse distance algorithm system (SigmaPlot, 1994), which evaluated every original data point, interpolated it, and thus converted the original 3D scatter data into a Cartesian mesh plot (Fig. 7). This allows for increased predictive power within the tested ranges. Because interpolated data points are graphed as the intersection of the mesh grid, pinpointing predicted values within this mesh is greatly simplified. As expected, increases in temperature and oxygen levels generally resulted in increases in the rates of physiological processes.

3.1. Temperature effect

The regulatory mechanisms underlying the relationship between growth rate and temperature are likely related to the enzymatic modulation of metabolic processes (Sumper, 1992; Al-Asgah and Ali, 1997). The general relationship between temperature and growth found in our experiment is illustrated in Fig. 7. There was very limited WG in fish held at the lowest temperature (15.7°C); above this, the total increment in weight increased with temperature. The results of the present study are in line with typical rate–temperature curves for warmwater species (West, 1965; Andrews and Stickney, 1972; Cox and Coutant, 1981; Cuenco et al., 1985; Carrieri et al., 1989; Tandler et al., 1989; Jobling, 1993; Iwata et al., 1994; Jobling, 1995; Requena et al., 1997). The growth rate of most warm water fish species increases with increasing temperature, to a value a few degrees below the upper lethal limit, provided the feed supply is not limited.
Fig. 7. Predictive Cartesian mesh plot for feed consumption based on results of fall and spring experiments. Grid was fitted to the predictive equation $FC = 0.163 - 0.001 * (T) - 0.002 * (O) + 0.00009 * (T * O)$, where $T$ = temperature and $O$ = dissolved oxygen. New data points were generated within tested ranges only (15–32°C and 30–100% oxygen saturation) through the use of the inverse distance algorithm system (SigmaPlot, 1994).

(Corey et al., 1983; Heap and Thorpe, 1987; Talbot, 1993). Such temperature-dependent increase in growth rate reflects increases in appetite, foraging efficiency, and biochemical reaction rates within the thermal tolerance range of the fish (Brett and Groves, 1979; Cossins and Bowler, 1987; Jobling, 1993). Maximum growth rate for the present experiment was achieved at approximately 28°C. According to Jobling (1993), appetite peaks at temperatures approaching the upper thermal tolerance limit of fish species falling dramatically above the optimum and decreasing more gradually below the optimum. At higher water temperatures, fish feed more vigorously and their digestive processes are accelerated (Cossins and Bowler, 1987) as was observed in the present study. Heap and Thorpe (1987) observed that turbot and turbot-brill hybrids grew faster at higher environmental temperatures, mainly because of much improved appetite, but also perhaps due to an increase in feed efficiency. Cai and Curtis (1990), however, reported that growth rate and feed consumption, but not assimilation efficiency of triploid grass carp increased with environmental temperature.

3.2. Light-temperature cycling

In the present study, WG was greater during spring than during fall for equivalent temperature/DO regimes (Fig. 3). Increasing photoperiod has been shown to increase
growth rates of several fish species such as juvenile Atlantic salmon and green sunfish (Jobling, 1993). Photoperiod could act as an inducer of daily rhythms observed in fish hormonal secretions (Requena et al., 1997). Corroborative evidence for the growth-promoting effect of light-temperature cycling has been demonstrated in studies with juvenile turbot, reared under different temperature and photoperiod regimes (Imsland et al., 1995). Also, juvenile sockeye salmon usually grow more rapidly under conditions of photothermal cycling than when held in continuously warm or cool water without photoperiod manipulation (Biette and Green, 1980; Jobling, 1995).

3.3. Oxygen effect

Increasing DO, up to some limiting value, results in enhanced growth of fish (Brett and Groves, 1979; Cuenco et al., 1985; Neill and Bryan, 1991). The association between weight gain and DO inferred for channel catfish in this study (Eq. (1)) is in agreement with that measured for largemouth bass (Stewart et al., 1967), common carp (Chiba, 1966), coho salmon (Hermann et al., 1962; Fisher, 1963), northern pike (Adelman and Smith, 1970) and brook trout (Whitworth, 1968).

Fish need oxygen to aerobically generate energy for body maintenance, locomotion and biosynthetic processes (Van Dam and Pauly, 1995). The sharp limitation of WG brought about by lowest values of DO in the present study (Fig. 4) can be explained by the effects of oxygen availability on appetite, FE and metabolism. Attempts have been made to determine levels of DO at which FI and growth become affected (Hogendoorn et al., 1983; Cui and Wootton, 1988). According to Cuenco et al. (1985), increasing DO up to some limiting level, at constant levels of all other factors, increases feed consumption. In the present study, limiting DO levels appeared to be around 70% air saturation for both spring and fall regimes. Below this level, FI values were sharply reduced and temperature seemed to have lesser influence on the fish’s appetite. Similar results have been obtained with rainbow trout (Jobling, 1993) reared under various conditions of DO. In that case FI was reduced when the DO fell below 60% air saturation. Also, results from the present experiment corroborate those of Andrews and Matsuda (1975), who showed reduced rates of FI and WG of channel catfish held at 26°C in water with 60% air saturation. Taken together, these data appear to indicate that DO below 70% air saturation limits feed consumption of channel catfish. Data relating limiting DO levels for FI in other species of fish are sparse, but from the evidence available it appears that limiting levels of DO are usually between 50 and 70% air saturation, with values for salmonids being towards the top end of the range (Jobling, 1995). It is important to state that the above suggested limiting level of oxygen saturation was determined for channel catfish under conditions of unrestricted feeding and, consequently, the level of DO that limits growth would be gradually reduced as feed becomes more restricted.

The relationship between WG and DO for channel catfish (Eq. (1)) is consistent with that measured for coho salmon by Fisher (1963). Garces-Botacio (1991) hypothesized that the effect of DO on feed consumption of the marine red drum was in part an effect on appetite. This relationship indeed may follow a similar pattern for various fish species. Reduced DO may lead to restriction of feeding activity, and/or changes in
digestion and assimilation efficiency. The reduction in FI rates found in the present study also can be explained by the effects of insufficient DO in slowing stomach evacuation (Smith, 1989; Becerra, 1998).

The rate of oxygen uptake by channel catfish has been evaluated for fed and unfed individuals (Andrews and Matsuda, 1975). The oxygen consumption value for satiated, 100-g fish was 1.45 times higher than that of unfed fish (0.81 and 0.56 g O$_2$/kg fish/h, respectively). During unfed conditions, lipid and protein oxidation account for 90–95% of total oxygen use (Van Dam and Pauly, 1995); whereas, in fed fish, amino acid oxidation replaces lipid oxidation (Dutta, 1994). According to Jobling (1981b; 1983) increased postprandial oxygen demand should be attributed mostly to digestive and post-absorptive effects, with only a minor fraction being ascribed to peristalsis and enzymatic secretions. It has been determined that high-protein diets notably increase oxygen consumption and specific dynamic action (SDA) (Matty and Lone, 1985). In the present study, differences in oxygen consumption were suggested by the depression in DO after feeding. Magnitudes of the depression indicated that channel catfish subjected to the +3°C, 100% air-saturation treatment that had a greater FI had oxygen consumption rates about 1.5 times greater than those of fish in the −3°C, 100% regime. These results are entirely consistent with those of Andrews and Matsuda (1975).

3.4. Weight gain and feed intake

Channel catfish in the present study grew fastest when water temperature was between 27 and 28°C. Generally, channel catfish do not feed consistently in ponds when water temperature drops below 21°C. Although they will feed at temperatures as low as 10°C, the amount and frequency of feeding are greatly reduced. Therefore, in cooler water, growth rate is markedly depressed. The most favorable temperature indicated above is slightly lower than that proposed by Andrews and Stickney (1972), who suggested “approximately” 30°C as the optimal temperature for catfish growth. This is probably influenced by differences in fish size (4 vs. 15 g in the present experiment). It is generally accepted that as a fish increases in size, its temperature optimum for maximum growth shifts to lower temperatures (Elliott, 1976; Brett, 1979; Cuenco et al., 1985; Jobling, 1995; Koskela et al., 1997).

Growth of fish is largely dependent on consumption of feed, its assimilation and conversion into body tissues (Nikolski, 1963; Brett and Groves, 1979; Dutta, 1994; Burel et al., 1996). It is clearly evident from the present data that growth rate was strictly dependent on FI. The slower growth rates in treatment −3°C, 30% (in comparison with +3°C, 100%) were due mainly to lower FI. A similar relation of growth to rate of FI has been demonstrated in largemouth bass (Thompson, 1941), brown trout (Pentelow, 1939; Elliott, 1975, 1976), sockeye salmon (Brett et al., 1969; Brett, 1971; Brett and Shelbourne, 1975; Biette and Green, 1980), common carp (Huismann, 1974), margined sculpin (Davis and Warren, 1965), coho salmon (Stauffer, 1973), channel catfish (West, 1965; Andrews and Stickney, 1972) and striped bass (Cox and Coutant, 1981).

To prevent feed limitation and excessive competition, the present study provided a temporal ‘clumping’ of feed supply. Consequently, dominant individuals, if any, were
unable to defend the feed source and other fish within the group were able to obtain
their fair share of the supplied feed. Under this experimental protocol, there was no
social hierarchy established and fish weight dispersion was limited. It has been demon-
strated that high feeding rates usually result in reduced individual growth variation
(Fauconneau et al., 1998).

Because feed supply was not limiting in the present study, feed consumption was
positively correlated with ambient temperature and DO. Feed consumption was more
than two-fold higher at 28.8°C than at all temperatures below 22°C. Also, thermal
treatments combined with 30% air saturation of DO resulted in intake levels at the low
end of the spectrum, for both the spring and fall experiments (Fig. 2). The decrease in
appetite of fish was most evident for the low temperature/low oxygen treatments and
from a practical stand point, there could be a risk of overfeeding when water tempera-
ture drops below 20°C and DO levels decline below 60% air saturation. Feed intake is
regulated partially by the speed with which digesta pass through the gut, which, as
previously indicated, is affected both by temperature and DO. In a general way, passage
increases as temperature (Flowerdew and Grove, 1979; Kaushik, 1981) and DO increase.
Elevated water temperature generally increases metabolic energy demands; thus, high
feeding rates are typically required to meet these demands. At the same time, increased
metabolic rates require increased oxygen availability and transport rates (Van Dam and
Pauly, 1995).

The lowest FI (less than 1.4 g/100 g BW/day) was obtained in the present study
with the low temperature/low DO combination (Fig. 2). Feed intake progressively
increased with increases in temperature and DO, up to 5 g/100 g BW/day at 30°C and
100% air saturation. In this study, rates of FI are comparable to those measured by
Andrews and Stickney (1972) for channel catfish held at 26–27°C. These results also are
in agreement with those of Platt and Hausser (1978), who found increases in feeding rate
of *Tilapia zillii* when the temperature was changed from 28.8°C to 31.4°C and that at
higher or lower temperatures, feeding rate and swimming stamina were reduced.

Based on the preceding information and the general profiles of the Cartesian plot for
feed consumption (Fig. 7), it can be inferred that maximum FI rates (3.4–4.6 g/100 g
BW/day) are likely to occur at 31–32°C and 90–100% air saturation. A practical
application of these data indicate that a shift in environmental conditions from 31°C,
50% air saturation to 31°C, 70% could increase consumption rates from 1.7 to 3.1
g/100 g BW/day, almost a two-fold increase.

Results of the present study indicate that FI kept increasing up to a temperature
2–3°C higher than the optimum for channel catfish growth (e.g., 30 vs. 28°C). Because
temperature’s differential effects on standard and active metabolic rates (Neill and
Bryan, 1991), the optimum temperature for fish growth tends to be a few degrees lower
than the temperature at which FI is maximal (Brett, 1971; Flowerdew and Grove, 1979;
Keast, 1985; Xiao-Jun and Ruyung, 1992; Jobling, 1993; Koskela et al., 1997) and data
from the present study agree with this conclusion. These results are similar to those of
Woiwode and Adelman (1991) who reported that feed consumption of hybrid striped
bass increased with temperature up to 29.2°C; whereas, the optimum temperature for
growth was 26.8°C, and FE peaked at 21.2°C.
3.5. Feed efficiency

Feed efficiency depends on several factors including feeding level and water temperature (Jobling, 1993). In fish fed maximum rations, FE increases with increasing temperature up to a maximum and then decreases as temperature continues to rise. The best FE is generally found at a lower temperature than that for optimum growth (Elliott, 1976; Brett, 1979; Jobling, 1993, 1995). Results from the present study are in accordance with this. Feed efficiency was best (1.0 for spring and fall) for channel catfish held at 24–26°C (Fig. 6); whereas, the optimum temperature for growth was estimated to be around 28°C. The values of FE found for channel catfish followed a trend similar to the one reported for rainbow trout (Staples and Nomura, 1976; Makinen, 1994). It is generally accepted that adaptive mechanisms exist which regulate the capacity of fish to utilize feed for growth over a range of temperature, as described in other species, such as chinook salmon (Brett, 1971), walking catfish (Hogendoorn et al., 1983) and European minnow (Cui and Wootton, 1988).

3.6. Temperature–oxygen interaction

Step-wise regression analyses, indicated that the variables temperature, DO, and temperature * DO accounted for most of the variation in FI, WG, FE and PER of channel catfish in the present study. In general, the inclusion of such variables in the model resulted in highly significant \( (P < 0.0001) \) effects when evaluated for interaction. When all were included they raised \( R^2 \) to 0.92. Garces-Botacio (1991), when modeling the growth performance of red drum, found that DO and temperature were statistically more relevant than ammonia, nitrite, phosphorus, and pH. Thus, it seems evident from the present study that temperature, DO and their interaction directly affect the physiological patterns of juvenile channel catfish by altering the metabolic rate of this species. As each factor deviates from the optimal level it becomes more important in limiting responses such as FI, WG, FE and PER. For example, under conditions of low temperature, the ingestion rate is low despite high oxygen availability (Fig. 7). High DO by itself does not promote high FI because there is no need for high energy supply when the metabolism (temperature-controlled) is depressed. Similarly, when high temperatures induce increased metabolic rates, DO is needed to support high energy demands. Because the present experimental design included three fixed levels of DO and two of those were at or above adequate, it is reasonable that the observed relationship (Eq. (1)) involved a coefficient for temperature of a higher magnitude (1.50 fold) than the coefficient for DO.

On the other hand, when DO went below 70%, FI rates were drastically reduced and temperature seemed to have less influence on the amount of feed consumed. It is logical to assume that, given the opportunity, fish will choose the least compromised combination of these two factors. This assumption agrees with results of behavioral regulation studies reviewed by Brett (1979), Brett and Blackburn (1981), Jobling (1981a), Kellogg and Gift (1983) and Weber and Kramer (1983), and is consistent with the model proposed by Neill and Bryan (1991). Thus, the impression is gained that there is a close correspondence between environmental preferenda and the joint optima of temperature and DO needed to achieve maximal physiological performance.
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