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Comparative Analysis of Fatty Acid Profiles in Brains and Eyes of Five Economic Fish Species in Winter and Summer

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Abstract Fish brains and eyes are commonly consumed in China, however, their nutritional importance has not been evaluated. We investigated the fatty acid (FA) profiles in brains and eyes of five economically important fish species with different food habits (carnivorous, omnivorous, and herbivorous). The fatty acid profiles were also compared between winter and summer. The FA compositions of brains and eyes of carnivorous and marine fishes were similar, and differed from those of omnivorous and herbivorous freshwater fishes. In winter, there were higher proportions of n-3 polyunsaturated fatty acids in brains and eyes of carnivorous and marine fishes than in those of omnivorous and herbivorous freshwater fishes; the magnitude of this difference was smaller in summer. The FA compositions of brains and eyes of these five fishes were comparable to those reported for their fillets in previous studies. Therefore, fish brains and eyes are not more nutritious than fillets of the same species.

Keywords: *fatty acid composition, brain, eyes, fishes, seasonal changes, n-3 polyunsaturated fatty acid (PUFA)*

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1. Introduction

The potential health benefits of fish consumption are mainly attributed to *n*-3 highly unsaturated fatty acids (HUFAs) such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids play roles in protection against cardiovascular disease (CVD), insulin resistance, and systemic inflammatory diseases [1]. Therefore, the fatty acid profiles of edible parts of fish are one of the main aspects of their nutritional value.

Most people consume fish fillets, rather than other parts of the fish. For most fish species, fatty acid composition data has been obtained for their fillet tissues. However, other fish organs are also consumed in some parts of the world. In China, fish brains and eyes are commonly consumed, especially by children. In Chinese culture, consumption of fish brains and eyes is believed to make children cleverer. If the proportion of *n*-3 HUFAs is higher in brain and eye tissues than in fillet tissues, then the traditional consumption of brains and eyes would be supported by modern nutritional theory that consumption of *n*-3 HUFA-rich tissues could benefit neural system development in young children. There is a higher proportion of *n*-3 HUFAs in neural tissues than in muscle in mammals and human [2]. However, it is unknown whether the fatty acid composition differs between neural tissues and muscle tissues in fishes.

Previous studies have indicated that the fatty acid profile in fish tissues varies depending on food habit and environmental factors, such as temperature and salinity [3,4,5]. Studies on mammals have shown that the fatty acid composition is more stable in neural tissues than in other organs [6], but this has not been fully investigated in fishes.

The aims of this study were to determine the fatty acid profile in brains and eyes of some commonly consumed fish species, and to determine whether these profiles are affected by the food habit and/or the environment of the fish. We selected five fish species with different food habits and environments for these analyses. We purchased the fish from local markets in Shanghai in winter and summer, and analyzed the fatty acid compositions of their eyes and brains.

2. Materials and Methods

2.1. Fish and Sampling

The five fish species selected in the present study are large yellow croaker (*Pseudosciaena crocea*) which is a marine carnivorous fish, silvery pomfret (*Pampus argenteus*) which is a marine carnivorous fish too, river eel (*Anguilla japonica*) which is a freshwater carnivorous fish, tilapia (*Oreochromis mossambicus*) which is a freshwater omnivorous fish, and grass carp (*Ctenopharyngodon idellus*) which is a freshwater herbivorous fish. Fishes were bought from three separated local markets at Minhang, Putuo and Huangpu Districts in Shanghai in January in winter and July in summer 2013, and the corresponding temperatures were between 1 to 9°C and 29 to 39°C, respectively. The basic biological characteristics of all collected fish are listed in Table 1.

Table 1. The basic biological and sampling information of five fish species

Common name	Species name	Habitat	Food habits	Reproduction	Living environment	Sampling season	Average fish wet weight (g)	Average fish total length (cm)	Number tested
Large yellow croaker	*Pseudosciaenacrocea*	Pelagic	Carnivorous	Summer	Marine	Winter	0.39±0.01	29.77±0.43	12
						Summer	0.34±0.02	29.75±0.68	12
Silvery pomfret	*Pampusargenteus*	Pelagic	Carnivorous	Summer	Marine	Winter	0.15±0.01	20.85±0.46	16
						Summer	0.11±0.00	17.71±0.95	13
River eel	*Anguilla japonica*	Pelagic	Carnivorous	Autumn	Freshwater	Winter	0.58±0.01	67.96±1.58	10
						Summer	0.56±0.03	63.59±1.35	10
Tilapia	*Oreochromismossambicus*	Pelagic	Omnivorous	Spring-autumn	Freshwater	Winter	0.47±0.02	27.30±0.53	12
						Summer	0.46±0.02	27.85±0.39	12
Grass carp	*Ctenopharyngodonidellus*	Pelagic	Herbivores	Spring	Freshwater	Winter	1.43±0.08	47.07±0.88	9
						Summer	1.47±0.08	50.10±0.64	10

The fish samples were immediately transported to the lab at East China Normal University, and the eyes and brains from 9-12 fish were rapidly taken and stored at -80°C until analysis.

2.2. Lipid Extraction and Fatty Acid Analysis

Total lipids of eyes and brains were extracted according to Bligh & Dyer (1959) [7]. Fatty acids from lipid samples were methylated using 10% potassium hydroxide in methanol for 1 h at room temperature. FA methyl esters were then analyzed and quantified using a Hewlett-Packard HP-5890 gas chromatograph in a cross-linked 5% phenylmethyl silicone gum phase column (L=25m, ID=0.32mm, DF=0.25μm, HP-Ultra 2, with nitrogen as the carrier gas), with flame ionization detection. Injector and detector temperatures were 280 and 300°C, respectively. The column temperature set at 190°C was then risen to 260°C (2°C/min) and held for 5 min. Results are expressed as the percentage of each FA with respect to total FA.

2.3. Statistical Analysis

Statistical analyses were performed using SPSS 19.0 for Windows (SPSS Inc., Chicago, IL). All analytical determinations were performed in triplicate and the mean values were reported. The average results of peak area are offered as means ± SE. The percentages of fatty acid were firstly tested by analysis of variance (ANOVA) and the differences between means were evaluated using Duncan's multiple test or T-test at $p<0.05$. Principal component analysis (PCA) was performed using the MATLAB environment.

3. Results

3.1. Fatty Acid Composition of Fish Brains in Winter and Summer

Table 2 shows the 18 main fatty acids in the brains of the five fish species in winter. A PCA analysis indicated that carnivorous fishes (large yellow croaker, silvery pomfret, and river eel) had a similar fatty acid composition pattern, which differed from that of omnivorous (tilapia) and herbivorous fishes (grass carp) (Figure 1a). Specifically, large yellow croaker, silvery pomfret, and river eel contained higher proportions of saturated fatty acids (SFA) (mean SFA, 38.39%, 48.14%, and 40.20%, respectively), higher proportions of *n*-3 polyunsaturated fatty acids (PUFAs) (mean *n*-3 PUFAs, 22.01%, 15.80%, and 16.82%, respectively), higher proportions of EPA+DHA (mean, 18.14%, 12.06%, and 13.38%, respectively), higher *n*-3/*n*-6 ratios (mean, 9.35, 35.63, and 27.03, respectively), and lower proportions of *n*-6 PUFAs (mean, 2.35%, 0.44%, and 0.62%, respectively), compared with their respective mean values in omnivorous (tilapia) and herbivorous (grass carp) fishes (SFA, 33.7% and 27.77%; *n*-3 PUFA, 8.26% and 7.25%; EPA+DHA, 3.94% and 2.71%; *n*-3/*n*-6 ratio, 0.44 and 0.41; *n*-6 PUFA, 18.73% and 17.52%, respectively). Of the three carnivorous fishes, large yellow croaker had the highest proportions of EPA, *n*-3 PUFA, and *n*-6 PUFA, and the lowest *n*-3/*n*-6 ratio.

Table 2. Fatty acid composition of fish brains in winter and summer

	Large yellow croaker	Silvery pomfret	River eel	Tilapia	Grass carp
In winter					
C14:0	2.49 ±0.27b	1.03 ±0.15a*	1.53 ±0.36a	2.33 ±0.13b**	1.39±0.13a *
C15:0	0.13 ±0.13	0.22 ±0.12	0.04 ±0.04	/	/
C16:0	27.20 ±0.23b**	27.83 ±2.9b	27.06 ±3.03b	23.73 ±0.42ab	20.71± 0.28a
C16:1	8.95± 0.64a	2.79 ±0.59c	5.61 ±0.74b	3.57 ±0.06c	6.07 ±0.10b*
C17:0	0.74 ±0.02ab	1.25 ±0.14bc*	1.67 ±0.37c	0.07 ±0.03a**	0.27 ±0.24a
C17:1	0.26 ±0.02	/	0.45 ±0.06	0.02 ±0.19	0.06 ±0.04
C18:0	7.83 ±0.70ab*	17.29 ±2.26c	9.88 ±0.20b	7.58 ±0.56ab	5.31 ±0.41a*
C18:1n-9t	0.07 ±0.04	/	/	0.30 ±0.02	0.19 ±0.01
C18:1n-9c	26.48 ±0.45a**	31.60 ±0.54b	34.95 ±1.18c	33.78 ±1.00bc	39.53 ±0.30d
C18:2n-6c	1.16 ±0.15a	0.20 ±0.10a	0.62 ±0.14a	17.56 ±1.37b	16.71 ±1.43b
C18:3n-3	0.67± 0.06b**	0.18 ±0.18a	0.09 ±0.06a	2.12 ±0.15d*	1.36 ±0.08c
C20:1n-9	1.42 ±0.21	0.92 ±0.25	1.25 ±0.18	1.22 ±0.14	1.42 ±0.02
C20:2	0.62 ±0.10	/	/	0.90 ±0.07	0.62 ±0.02
C20:3n-3	1.78 ±0.18*	2.25 ±0.43	2.98±0.22 *	1.67 ±0.26	3.02 ±0.87
C20:3n-6	0.58 ±0.16	0.25 ±0.13	/	0.17 ±0.06	0.11 ±0.02
C20:5n-3	5.05 ±0.22d*	1.97 ±0.49c	1.16 ±0.15b	0.18 ±0.01a	0.15 ±0.01a
C22:5n-3	1.42 ±0.12b	1.31 ±0.52b	0.38 ±0.12a	0.53 ±0.02a	0.16 ±0.01a
C22:6n-3	13.09 ±0.66b**	10.09 ±2.27b	12.22 ±2.44b	3.76 ±0.80a	2.57 ±0.79a
SFA	38.39 ±0.31b**	48.14 ±4.81c	40.20 ±3.2bc	33.70 ±0.90ab	27.77 ±0.43a
MUFA	37.25 ±1.05a**	35.61 ±1.57a	42.26 ±1.02b	39.31 ±1.24bc	47.46 ±0.35c
PUFA	24.36 ±0.92c**	16.25 ±3.63b	17.45 ±2.96b	26.99 ±1.42a	24.77 ±0.24c
N-3	22.01 ±0.96 c **	15.80 ±3.54b	16.82 ±2.88b	8.26 ±1.03a	7.25 ±1.58a
N-6	2.35 ±0.23b	0.44 ±0.09a	0.62 ±0.14a	18.73 ±1.47c	17.52 ±1.47c
EPA+DHA	18.14 ±0.77c**	12.06 ±2.70c	13.38 ±2.54c	3.94 ±0.81b	2.71 ±0.78a
N3/N6	9.35 ±1.08b	35.63 ±2.93c*	27.03 ±6.28c	0.44 ±0.08a	0.41 ±0.14a
In summer					
C14:0	2.64±0.54c	2.17±0.28bc	1.52±0.07ab	1.34±0.15ab	0.87±0.12a
C15:0	0.21±0.21	0.56±0.06	0.03±0.03	/	/
C16:0	35.22 ±1.55b	35.11±1.17b	31.98±1.01b	22.88±0.44a	19.97±0.30a
C16:1	8.99±1.27c	2.97±0.50a	5.34±0.47b	2.95±0.23a	3.40±0.30ab
C17:0	0.75 ±0.06a	1.87±0.06bc	2.53±0.42c	1.31±0.10ab	1.04±0.33a
C17:1	/	0.04±0.04	/	/	0.21±0.09
C18:0	11.82 ±1.01a	19.44±1.44b	11.44±0.56a	9.60±0.11a	9.00±0.79a
C18:1n-9t	0.05±0.05	0.04±0.04	0.00±	0.19±0.11	0.10±0.05
C18:1n-9c	32.96 ±1.01ab	29.26±1.49a	36.36±1.92b	35.96±0.93b	38.12±2.16b
C18:2n-6c	0.75±0.25a	0.38±0.10a	0.91±0.33a	14.10±1.06b	16.15±1.06b
C18:3n-3	0.06 ±0.06a	0.06±0.03a	0.10±0.07a	1.47±0.06b	1.76±0.29b
C20:1n-9	1.33±0.13c	0.50±0.02a	0.77±0.01ab	1.13±0.14c	1.10±0.14bc
C20:2	0.52±0.29	/	/	0.68±0.05	0.58±0.02
C20:3n-6	0.41±0.08	0.06±0.03	/	0.48±0.48	0.14±0.09
C20:3n-3	0.66 ±0.23a	1.92±0.17b	2.34±0.08b	2.15±0.22b	2.66±0.56b
C20:5n-3	0.79 ±0.38b	0.86±0.07b	0.45±0.14b	/	0.10±0.05a
C22:6n-3	2.55 ±1.27a	4.43±0.38ab	6.22±0.66b	5.13±0.65ab	4.70±1.55ab
SFA	50.92±1.11c	59.14±1.75d	47.51±1.25c	35.33±0.74b	30.88±0.81a
MUFA	43.33 ±0.56b	32.80±1.97a	42.47±2.34b	40.22±1.26b	42.93±2.51b
PUFA	5.75±1.58a	8.06±0.27a	10.02±1.19a	24.45±1.23b	26.19±1.70b
N-3	4.07±1.60a	7.62±0.17ab	9.11±0.87b	9.19±0.96b	9.32±2.43b
N-6	1.68 ±0.49a	0.44±0.10a	0.91±0.33a	15.26±0.63b	16.87±1.00b
EPA+DHA	3.34±1.65	5.29±0.35	6.67±0.80	5.13±0.65	4.80±1.55
N3/N6	3.50 ±2.40b	19.01±4.01c	12.56±3.94c	0.60±0.06a	0.57±0.17a

Values are mean ± S.D. Mean values within a row with unlike letters are significantly different ($P < 0.05$).* or ** means significantly ($P < 0.05$) or very significantly ($P < 0.01$) different as compared withthe corresponding fatty acid in summer.

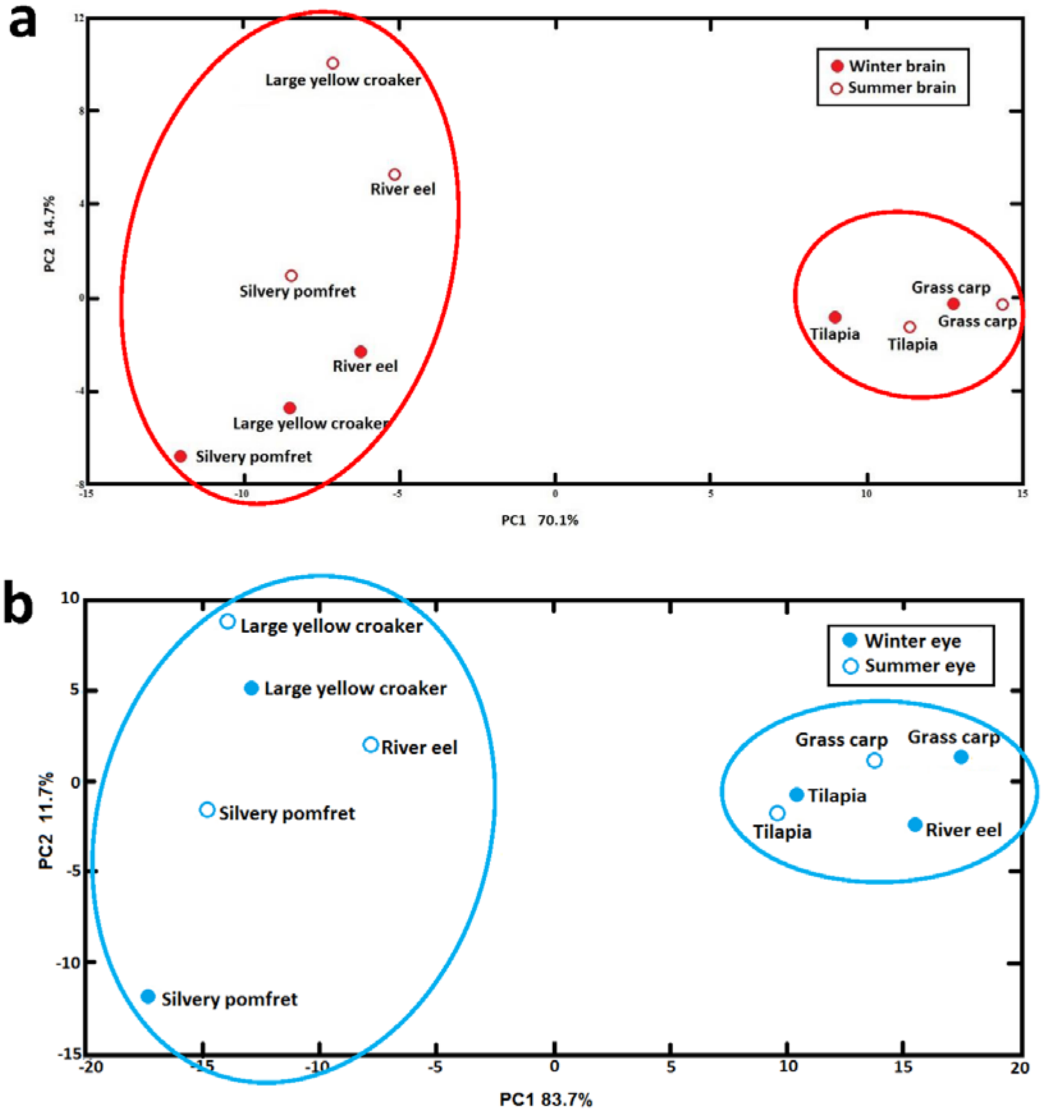

Figure 1. PCA analysis of fatty acid composition in brains and eyes of five economic fish species

In summer, the general differences in fatty acid composition between carnivorous fishes and non-carnivorous fishes still existed (Figure 1a). However, there were no significant differences in the proportions of most specific fatty acids, especially *n*-3 PUFAs and EPA+DHA, between carnivorous and non-carnivorous fishes (Table 2). In summer, yellow croaker, silvery pomfret, and river eel showed higher proportions of SFAs (50.92%, 59.14%, and 47.51%, respectively), higher *n*-3/*n*-6 ratios (3.5, 19.01, and 12.56, respectively) and lower proportions of *n*-6 PUFAs (1.68%, 0.44%, and 0.91%, respectively), compared with their corresponding values in tilapia and grass carp (SFA, 35.33% and 30.88%; n-3/n-6 ratio, 0.6 and 0.57; *n*-6 PUFAs, 15.26% and 16.87%, respectively). Of the three carnivorous fishes, large yellow croaker had the lowest *n*-3/*n*-6 ratio, because the proportion of *n*-3 PUFAs was relatively low and that of *n*-6 PUFAs was relatively high. Tilapia and grass carp showed similar fatty acid compositions.

We determined whether the main fatty acids were correlated with food habit (carnivorous, herbivorous, omnivorous) or environment (freshwater or sea water) (Table 4). The proportions of SFAs, MUFAs, *n*-3 PUFAs, *n*-6 PUFAs, and EPA+DHA in fish brains were significantly correlated with diet and with environment in winter. In summer, there were no significant correlations between MUFA and food habit or environment, between *n*-3 PUFAs and food habit, or between EPA+DHA and food habit or environment.

To compare the effects of season on the fatty acid composition of brains, we compared the fatty acid composition for the same fish species between winter and summer (see Table 2). There were significant differences between winter and summer in the proportions of seven fatty acids (16:0, 18:0, 18:1*n*-9c, 18:3*n*-3, 20:3*n*-3, 20:5*n*-3, 22:6*n*-3) in large yellow croaker, two fatty acids (14:0, 17:0) in silvery pomfret, one fatty acid (20:3*n*-3) in river eel, three fatty acids (14:0, 17:0, 18:3*n*-3) in tilapia, and three fatty acids (14:0, 16:1, 18:0) in grass carp. Figure 2 shows the trends in the differences in brain fatty acids between winter and summer. The proportion of SFAs tended to increase from winter to summer in carnivorous fishes, but was similar in winter and summer in omnivorous and herbivorous fishes. The proportion of MUFAs in the brain was significantly higher in summer than in winter for large yellow croaker, but lower in summer than in winter in the other fishes. The proportions of *n*-3 PUFA and EPA+DHA in brains were lower in summer than in winter in the three carnivorous fishes, but higher in summer than in winter in tilapia and grass carp.

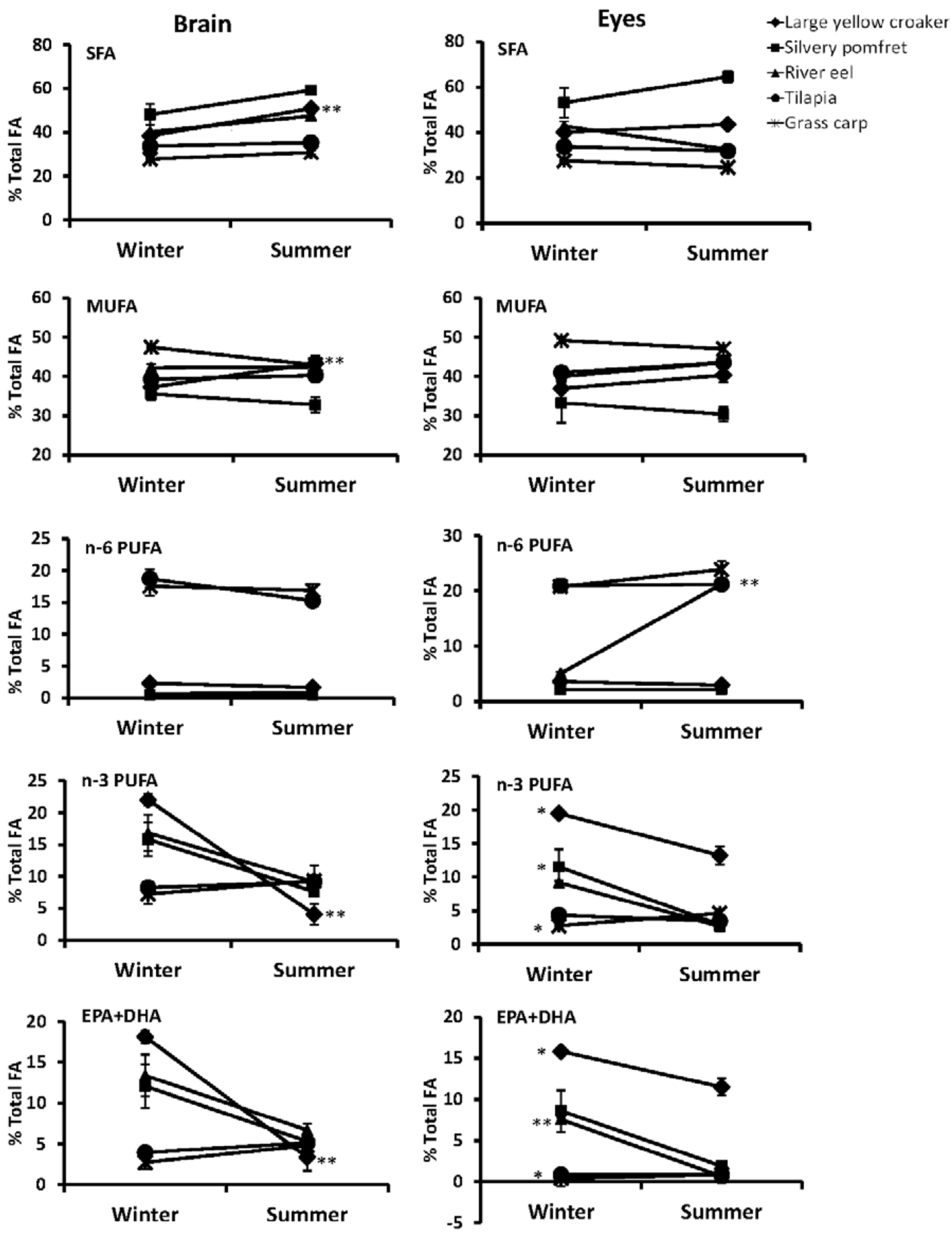

Figure 2. Seasonal alteration of main fatty acids percentages in brains and eyes of five economic fish species. * or ** means significant (P < 0.05) or very significant (P < 0.01) difference between two seasons

3.2. Fatty Acid Composition of Fish Eyes in Winter and Summer

We determined the main fatty acids in the eyes of the five fish species in winter (Table 3). A PCA analysis showed that carnivorous fishes had a similar fatty acid composition pattern, which differed from that of omnivorous and herbivorous fishes (Figure 1b). Specifically, large yellow croaker, silvery pomfret, and river eel contained higher proportions of *n*-3 PUFAs (mean, 19.49%, 11.52%, and 9.2%, respectively), higher proportions of EPA+DHA (mean, 15.83%, 8.6%, and 7.56%, respectively), higher *n*-3/*n*-6 ratios (mean, 5.42, 5.44, and 1.82, respectively), and lower proportions of *n*-6 PUFAs (mean, 3.59%, 2.12%, and 5.04%, respectively), compared with their respective values in tilapia and grass carp (*n*-3 PUFAs, 4.35% and 2.79%; EPA+DHA, 0.86% and 0.42%; *n*-3/*n*-6 ratio, 0.21 and 0.13; *n*-6 PUFAs, 20.93% and 20.80%, respectively). Of the three carnivorous fishes, large yellow croaker had the highest proportions of EPA, DHA, and *n*-3 PUFAs.

Table 3. Fatty acid composition of fish eyes in winter and summer

	Large yellow croaker	Silvery pomfret	River eel	Tilapia	Grass carp
In winter					
C14:0	3.62±0.05ab	6.05±1.67b	3.95±0.31ab	2.66±0.15a	1.46±0.05a
C15:0	0.34±0.17	/	0.20±0.01	0.11±0.11	0.04±0.04
C16:0	29.78±0.38bc*	34.53±4.06c	32.01±1.18c	24.84±0.49ab	21.78±0.21a*
C16:1	11.15±0.20c	4.28±0.78a	7.18±0.97b	3.88±0.08a	6.18±0.24b**
C17:0	0.85±0.04b	2.09±0.24c	0.13±0.07a	0.12±0.008a	0.07±0.03a
C17:1	0.37±0.01	0.10±0.06	0.04±0.04	/	/
C18:0	5.23±0.08a**	10.28±1.15b	6.37±2.37a	5.73±0.20a	3.99±0.03a
C18:1n-9t	0.10±0.005a	0.08±0.004a	0.03±0.03a	0.35±0.003c	0.22±0.01b
C18:1n-9c	23.58±0.25a	26.43±4.61ab	31.91±1.33bc	35.00±1.12cd	41.35±0.35d
C18:2n-6c	1.70±0.47a*	0.91±0.32a	4.77±0.40b**	19.75±1.16c	19.87±0.41c
C18:3n-3	0.99±0.07b*	0.72±0.10a*	0.54±0.01a	2.42±0.14d	1.40±1.40c*
C20:1n-9	1.72±0.27	1.68±0.67	0.77±0.09	1.49±0.11	1.35±0.01
C20:2	0.91±0.04a	0.30±0.05b*	0.11±0.06a	0.97±0.06a	0.65±0.01c
C20:3n-3	1.20±0.07	0.96±0.56	0.84±0.13	0.61±0.04*	0.89±0.03
C20:3n-6	0.83±0.26	0.41±0.16	/	0.08±0.05	0.22±0.16
C20:4n-6	/	0.49±0.49	/	/	/
C20:5n-3	5.33±0.01c*	2.03±0.54b*	1.18±0.32b*	0.19±0.02a	0.11±0.01a**
C20:6n-3	1.47±0.12b*	1.25±0.44b*	0.26±0.05a*	0.46±0.22a	0.09±0.01a
C22:6n3	10.50±0.48c*	6.56±1.98b*	6.38±0.31b**	0.67±0.09a	0.31±0.03a*
SFA	39.96±0.55b	53.07±6.66c	42.68±2.22b	33.70±0.62ab	27.42±0.29a
MUFA	36.95±0.35a	33.29±5.08a	39.97±1.85a	41.02±1.19a	49.15±0.59b
PUFA	23.09±0.20b	13.64±2.78a*	14.24±0.25a	25.28±1.46b	23.59±0.55b
N-3	19.49±0.35c*	11.52±2.62b*	9.20±0.27b*	4.35±0.27a	2.79±0.10a*
N-6	3.59±0.18ab	2.12±0.35a	5.04±0.31b**	20.93±1.19c	20.80±0.54c
EPA+DHA	15.83±0.49c	8.60±2.51b	7.56±0.18b**	0.86±0.08a	0.42±0.04a*
N3/N6	5.42±0.35b*	5.44±1.34b	1.82±0.15a**	0.21±0.00a	0.13±0.01a
In summer					
C14:0	3.33±0.17	3.19±0.161	1.61±0.82	2.25±0.30	1.32±0.15
C15:0	0.23±0.23a	0.87±0.22b	0.14±0.08a	0.28±0.03a	0.03±0.03a
C16:0	32.52±0.99c	40.69±0.1.03d	24.93±0.46b	23.68±0.47b	18.98±0.60a
C16:1	11.00±0.68c	3.92±0.71a	5.68±0.18b	3.99±0.26a	4.31±0.31ab
C17:0	0.88±0.06	1.81±0.27	0.08±0.05	0.02±0.02	/
C17:1	0.11±0.07	/	0.02±0.02	0.03±0.03	/
C18:0	6.46±0.04a	17.94±3.06b	5.52±1.53a	5.48±0.13a	4.16±0.53a
C18:1n-9t	0.11±0.06a	0.08±0.08a	0.14±0.08a	0.37±1.23b	0.20±0.02ab
C18:1n-9c	27.36±1.03a	25.36±1.47a	36.94±0.44b	37.21±1.23b	41.20±0.87c
C18:2n-6c	1.68±0.69a	1.88±0.78a	26.85±0.74b	19.19±1.28b	23.12±1.51b
C18:3n-3	0.45±0.23a	0.14±0.144a	1.63±0.83ab	1.47±0.67ab	2.57±0.41b
C20:1n-9	1.50±0.15bc	0.97±0.16ab	0.74±0.13a	1.67±0.29c	1.18±0.19abc
C20:2	0.35±0.35a	0.07±0.07a	0.26±0.13a	1.01±0.13b	0.64±0.03ab
C20:3n-3	0.62±0.26ab	0.90±0.14ab	0.43±0.21a	0.64±0.03ab	1.02±0.09b
C20:3n-6	0.80±0.15	0.16±0.09	0.04±0.04	0.94±0.94	0.11±0.09
C20:4n-6	/	/	/	/	/
C20:5n-3	3.74±0.04b	0.31±0.04a	0.28±0.10a	0.14±0.08a	0.23±0.05a
C20:6n-3	0.68±0.34	/	/	0.49±0.11	0.17±0.02
C22:6n-3	7.76±0.04a	1.58±0.34a	0.37±0.21a	0.71±0.20a	0.65±0.10a
SFA	43.46±0.80c	64.58±2.84d	32.52±1.03b	31.78±0.71b	24.49±1.04a
MUFA	40.33±1.82b	30.37±1.87a	43.55±0.16ab	43.58±0.98ab	47.01±0.80c
PUFA	12.52±4.68ab	5.05±1.08a	17.44±7.26abc	24.64±1.28bc	28.50±1.83c
N-3	13.26±1.32b	2.94±0.42a	2.70±0.81a	3.45±0.34a	4.63±0.59a
N-6	2.95±0.32a	2.11±0.81a	21.23±0.70b	21.20±1.21b	23.87±1.49b
EPA+DHA	11.5±1.05b	1.90±0.31a	0.65±0.30a	0.85±0.28a	0.87±0.15a
N3/N6	3.29±1.74b	1.84±0.58ab	0.33±0.17a	0.16±0.02a	0.19±0.02a

Values are mean ± S.D. Mean values within a row with unlike letters are significantly different ($P < 0.05$). * or ** means significantly ($P < 0.05$) or very significantly ($P < 0.01$) different as compared withthe corresponding fatty acid in summer.

In summer, the fatty acid composition of eyes was similar in river eel, tilapia, and grass carp (Figure 1b). The fatty acid composition in summer differed between the marine fishes (large yellow croaker and silvery pomfret) and freshwater fishes (river eel, tilapia and grass carp). Specifically, large yellow croaker and silvery pomfret had higher proportions of EPA+DHA (11.5% and 1.9%, respectively), higher *n*-3/*n*-6 ratios (3.29 and 1.84, respectively), and lower proportions of *n*-6 PUFA (2.95% and 2.11%, respectively), compared with those in river eel, tilapia, and grass carp (EPA+DHA, 0.65%, 0.85%, and 0.87%; *n*-3/*n*-6 ratio, 0.33, 0.16, and 0.19; *n*-6 PUFA, and

21.23%, 21.20%, and 23.87%, respectively). Of the five fishes, large yellow croaker had the highest proportions of *n*-3 PUFAs and EPA+DHA, and the highest *n*-3/*n*-6 ratio.

Table 4 shows the correlations between the main fatty acids of fish eyes and food habit (carnivorous, herbivorous, omnivorous) or environment (freshwater or sea water). The concentrations of SFA, MUFA, *n*-3 PUFA, *n*-6 PUFA and EPA+DHA in fish eyes were significantly correlated with food habit and environment in winter. There were no significant correlations between *n*-3 PUFA and food habit, EPA+DHA and food habit in summer.

Table 4. Correlation analysis of selected nutrient *vs.* living environment and food habit, in brain and eyes of fish in winter and summer

Dependent variables		Independent variables	
		Food habits	Living environment
In brains			
SFA	In winter	0.001	0.02
	In summer	0.001	0.001
MUFA	In winter	0.002	0.002
	In summer	0.338	0.146
N3-PUFA	In winter	0.001	0.013
	In summer	0.178	0.027
N6-PUFA	In winter	0.001	0.012
	In summer	0.001	0.008
EPA+DHA	In winter	0.001	0.009
	In summer	0.847	0.259
In eyes			
SFA	In winter	0.001	0.018
	In summer	0.007	0.001
MUFA	In winter	0.001	0.011
	In summer	0.015	0.001
N3-PUFA	In winter	0.001	0.001
	In summer	0.425	0.004
N6-PUFA	In winter	0.001	0.002
	In summer	0.006	0.000
EPA+DHA	In winter	0.001	0.001
	In summer	0.137	0.005

Values in table are p values of correlations between dependent and independent variables.

We determined the effects of season on the fatty acid composition of eyes of the five fish species (Table 3). The fatty acid composition of fish eyes in tilapia and grass carp was comparable between winter and summer (Figure 2). For the three carnivorous fishes, the proportions of most *n*-3 PUFAs were significantly higher in winter than in summer, but the proportion of *n*-6 PUFA in river eel eyes was significantly higher in summer than in winter (5.04% in winter *vs*. 21.23% in summer). Figure 2 shows the seasonal trends in the main fatty acids in the eyes. These trends were similar to those observed for fatty acids in the brains, except for the higher proportion of *n*-6 PUFAs in river eel eyes in summer than in winter.

4. Discussion

Fish fillets are the main edible parts of fish, and are an important dietary source of *n*-3 PUFAs for consumers. Therefore, most studies on the fatty acid composition of fish tissues have focused on fish fillets [8,9,10]. In contrast, few studies have evaluated the fatty acid composition of fish brains and eyes [11,12]. The nutritional importance of consuming fish brains and eyes had not been evaluated previously.

Studies on mammals have indicated that neural tissues, including the brain and eye retina, contain higher concentrations of *n*-3 HUFAs than do other organs, and that *n*-3 HUFAs are specifically retained in these tissues even under dietary deprivation [13]. Mammals and human have a specific requirement for 18: 2*n*-6, and their muscles have low *n*-3 PUFA contents. The specific retention of high concentrations of *n*-3 HUFAs in mammalian neural tissues indicates that *n*-3 PUFAs are important components of neural tissues. Whereas *n*-6 fatty acids are essential for mammals, *n*-3 PUFAs are essential fatty acids for most fishes [14]. Fish fillets contain high proportions of *n*-3 PUFAs. Several studies have reported the *n*-3 PUFA composition of fillets for the five fish species that we studied. Those studies reported that the proportion of *n*-3 PUFAs was 19–24% in large yellow croaker [15], 15.37–25.26% in silvery pomfret [16], 15.22–19.64% in river eel [17,18], 3.1–15.9% in tilapia [19], and 9.7–16.8% in grass carp [20]. Comparison of the data obtained in the present study with those data indicates that the *n*-3 PUFA content is not higher in brains and eyes than in fillets. Furthermore, considering the tiny mass of brains and eyes, the specific consumption of brains and eyes is more likely based on a cultural tradition, rather than the nutritional value of these tissues.

Marine fishes generally contain a higher proportion of *n*-3 HUFAs than do freshwater fish. This typical fatty acid composition of marine fish results from the fatty acid composition of the marine phytoplankton that they consume [21]. Higher salinity also increases the proportion of *n*-3 HUFA, even within the same fish species [22]. Our findings are consistent with those studies. That is, there were higher proportions of *n-3* HUFAs in the two marine fishes (large yellow croaker and silvery pomfret) than in tilapia and grass carp. River eel, a freshwater fish, had a very similar fatty acid profile to that of marine fish, except for the fatty acid profile of eyes in summer. River eel is a catadromous fish; that is, it inhabits the sea during its early life stage (glass eel stage). Some studies have demonstrated that the capacity to biosynthesize long-chain PUFA (LCPUFA) in some fish, including salmon and Japanese eel, is more strongly affected by environmental and nutritional factors during their early life stage than during their adult stage [23,24].

Therefore, the characteristic marine fish fatty acid composition of river eel may be because it is catadromous.

As well as food habit and salinity, temperature is a key factor affecting the fatty acid composition of fish fillets [25,26]. However, the seasonal differences in the fatty acid profiles in fish brains and eyes had not been evaluated previously. In mammals, fatty acids are more stable in neural tissues than in other tissues [6]. This biochemical stability in the neural system could help to maintain a stable internal environment. The ability to maintain a stable environment is related to the homothermal mechanism in mammals and human. In contrast, fish are heterothermic organisms; that is, their body temperature fluctuates depending on the water temperature. This study is the first report that the *n*-3 PUFA content in brains and eyes of fishes, especially marine fishes, is higher in winter than in summer. However, the effects of season on the *n*-3 PUFA content in fish fillets vary depending on the species. In sardine and tilapia, the proportion of *n*-3 PUFAs in fillets negatively correlates with water temperature [5,26], similar to our results for fish brains and eyes. However, in anchovy and picarel, the reverse trend has been reported; that is, higher *n*-3 PUFA content in fillets in summer than in winter [5]. In croaker, the *n*-3 PUFA composition of fillets was reported to be similar in winter and summer [26]. HUFAs are necessary to maintain the fluidity of cellular membranes, especially in cold environments [27,28]. Therefore, fishes may need to synthesize more long-chain PUFA in neural tissues in winter than in summer to maintain sufficient membrane fluidity [29]. Our data show that the fatty acid composition of brains and eyes of tilapia and grass carp, which contained a high proportion of *n*-6 PUFAs, remained relatively stable regardless of the season. This suggests that in fishes, and especially in fish neural tissues, *n*-3 PUFAs, but not *n*-6 PUFAs, are more sensitive than other types of fatty acids to water temperature. This hypothesis should be tested in further studies.

5. Conclusion

We analyzed the fatty acid profiles in fish brains and eyes, and determined the effects of food habit and environment on the fatty acid profiles. The fatty acid profiles of brains and eyes were comparable to those reported for fillets of the same species. Therefore, specific consumption of fish brain and eyes will not confer any additional nutritional benefits compared with consuming fish fillets.

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Statement of Competing Interests

The authors have no competing interests.

Abbreviations

CVD, Cardiovascular disease; DHA, Docosahexaenoic acid; EPA, Eicosapentaenoic acid; FA, Fatty acid; HUFA, Highly unsaturated fatty acid; MUFA, Monounsaturated fatty acid; PUFA, Polyunsaturated fatty acid; PCA, Principal component analysis; SFA, Saturated fatty acid;

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