Lateral bias of agonistic responses to mirror images and morphological asymmetry in the Siamese fighting fish (*Betta splendens*)

Yuichi Takeuchi[a*], Michio Hori[a], Omar Myint[b] & Masanori Kohda[b]

[a]Department of Zoology, Graduate School of Science, Kyoto University, Oiwake-cho, Sakyo, Kyoto 606-8502, Japan; [b]Department of Biology and Geosciences, Graduate School of Science, Osaka City University, Sumiyoshi, Osaka 558–8585, Japan.

The number of text page: 32
The number of figures: 3
The number of tables: 1

Corresponding author: Yuichi Takeuchi
Department of Zoology, Graduate School of Science, Kyoto University,
Kitashirakawa-Oiwake, Sakyo, Kyoto. 606-8502, Japan
e-mail: yuichi@terra.zool.kyoto-u.ac.jp
Tel.: +81-75-753-4077
Fax: +81-75-753-4100

Abstract

Behavioural laterality (e.g., during social interactions) is often observed at the individual level in lower vertebrates such as fish, whereas population-level laterality is observed in many higher vertebrates. Population-level laterality can be explained mainly by internal factors (e.g., cerebral lateralization), whereas little is known about the behavioural mechanisms underlying individual-level laterality. Recently, it was revealed that many fish have asymmetrical body morphology, but the relationship between asymmetric morphology and social behaviours has been rarely examined. Here we report the relationship between lateralized eye use during aggressive displays (e.g., body posture) of male Siamese fighting fish, *Betta splendens,* toward their own mirror image and morphological asymmetry. Of 25 males, five exhibited significantly more leftward eye use during left displays, and eight males exhibited predominantly rightward eye use during right displays. Morphological measurement results for the craniovertebral angle and opercular area showed that the craniovertebral angle and opercular area displayed antisymmetry and fluctuating asymmetry, respectively. We found that lateralized eye use during agonistic responses by each fish was associated with the craniovertebral angle, but not with operculum size; lefties (left-curved body) showed mainly left eye use (during left-side displays), and righties (right-curved body) demonstrated the opposite. We suggest that antisymmetric morphologies, such as head incline, are potentially useful for studying the association between cerebral lateralization and individual laterality of behavioural responses. Further, we propose that in fish, morphological asymmetry is related to laterality in various behaviours.

Keywords: cerebral lateralization, eye use, aggressive display, behavioral laterality, betta, head incline, morphological asymmetry

Yuichi Takeuchi

Ph.D. Department of Zoology, Graduate school of Science, Kyoto University, Sakyo, Kyoto 606-8502, Japan.

Michio Hori

Professor. Department of Zoology, Graduate school of Science, Kyoto University, Sakyo, Kyoto 606-8502, Japan.

Omar Myint

Master of Sciense. Department of Biology and Geosciences, Graduate School of Science, Osaka City University, Sumiyoshi, Osaka 558–8585, Japan.

Masanori Kohda

Professor. Department of Biology and Geosciences, Graduate School of Science, Osaka City University, Sumiyoshi, Osaka 558–8585, Japan.

1. Introduction

Cerebral lateralization is well known among vertebrates, including fish [3, 33, 49, 50]. This lateralization appears to be important for enhancing the performance of complex behaviours. Specifically, it allows the brain to work simultaneously on different tasks [8, 14, 21, 35] and cope with divided attention [9, 32, 34]. Lateralization has been assessed in neurological investigations and behavioural experiments. In case of behavioural experiments, preferred limb and eye use in response to a situation can indicate the degree of cerebral lateralization (reviewed in [49]). Higher vertebrates mainly show behavioural laterality at the population level (i.e., most or all individuals of a population share the same bias), whereas lower vertebrates frequently show behavioural laterality at the individual level (i.e., the direction of bias differs among individuals, [3]). Behavioural laterality at the population level is considered to be evolutionarily meaningful; selective pressures for lateral specialization likely operated within the population [11]. In the case of individual-level laterality, however, behavioural bias is difficult to examine with respect to cerebral lateralization because each organism may be subjected to different developmental stressors, such that information processing differs between each individual, even within a species [2, 3]. Thus far, little is known regarding the purpose and mechanisms underlying behavioural laterality at the individual level. Additional investigations using several approaches are required to fully understand behavioural laterality.

Individual laterality is widespread among fish [3]. Fish eyes are laterally placed on the head, and each eye is exposed to a different visual field. Because visual pathways from each eye project almost exclusively to the contralateral hemisphere [51], transfer of information between the two hemispheres of the brain is low. Therefore, preferences in eye use are considered to be behavioural manifestations of right or left hemisphere specialization in the analysis of incoming visual information [47].

In some fish, individual laterality in foraging behaviours is correlated with morphological asymmetry, such as mouth dimorphisms (scale-eating cichlids, [18]; shrimp-eating cichlids, [45]; large-mouth bass, [25]). These fish exhibit skewed mouths that open either rightward (‘lefty’) or leftward (‘righty’), owing to asymmetrical joints of the lower jaws to the suspensorium. In addition, lefties have a C-shaped body with more developed left-side muscles and the left side of the fish’s head faces forward; righties are exactly opposite [25]. These fish show lateral bias in foraging behaviours that is correlated with morph type; lefties mainly approach from the left side of the prey animal and righties approach from the right side. Correlations between morph type and behavioural laterality of the scale-eater [18] and the shrimp-eater [45] are regarded as adaptations for predation efficiency. Mouth dimorphism is considered to be a genetic trait that is determined by a Mendelian system (one locus, two alleles), with the lefty morph dominant over the righty [18, 20, 38]. Recently, fish of various feeding guilds, e.g., herbivores, benthivores, and piscivores, have been documented to have the same type of mouth dimorphism. It has been suggested that asymmetric morphology in fish is correlated with a variety of behaviours [19]; however, the relationship between asymmetric morphology and behavioural laterality, excluding predation, remains to be clarified, with the exception of disassortative mating [44].

Laterality in social behaviours is observed in some vertebrates. Left eye/right hemisphere dominance in eliciting agonistic responses has been demonstrated in many vertebrates, such as baboons [5], chicks [37], lizards [10], and toads [30]. The right hemisphere is suggested to be responsible for the general assessment of novelty. Teleost Belontiidae males show strong agonistic responses at an individual level of lateralization when examining other individuals or their own reflection in a mirror [4, 6]. These fish prefer to use either the right or left eye individually in order to assess the opponent. Among Belontiidae fish, the Siamese fighting fish, *Betta splendens,* is highly aggressive in response to mirror reflections, and individuals show marked lateralization [6].

Individual laterality in behavioural responses may be explained by the "best side" hypothesis, which states that fluctuating asymmetry (FA) is related to behavioural bias [13]. Gross et al. [13] demonstrated that male guppies with asymmetric ornamental colours preferentially show their more colourful side to the female, and males with symmetric colours show both sides randomly. In the case of *B. splendens*, operculum size is considered to be important for aggressive and courtship displays, as fish remarkably erect the operculum during these social situations [40]. Therefore, male betta might preferentially display their best side (i.e., larger operculum) to the opponent during aggressive interactions. As a consequence, the fish uses the eye on its best side.

In this study, we examined lateralized eye preference at the individual level during agonistic displays in *B. splendens*. Furthermore, we examined the correlation between laterality in eye preference and morphological asymmetry.

2. Materials and Methods

2.1.Animals

Betta splendens males show intense aggressive behavioural patterns [40], and are widely used as a model species in research on the lateralization of aggressive interactions. For this study, 25 adult male fish were obtained from a local dealer. All experimental males had a similar body size (standard length: 31.33–38.44 mm). Fish were maintained individually in small plastic containers (10 × 10 × 15 cm) containing approximately 1 L of aged tap water. Water temperature was maintained at 25–26°C, and artificial light was provided for 12 h per day. The fish were fed dry fish food daily.

2.2. *Behavioural tests*

An octagonal shaped experimental tank (14.5 cm on a side) lined with mirrors was prepared. The apparatus was filled with water 12 cm deep. One fluorescent lamp (20 W) mounted 1.5 m above the tank provided illumination. The entire apparatus was kept in a darkened room to avoid any influence of the experimenters.

Each fish was introduced into the experimental tank with a small hand net made of fine mesh (10 cm in diameter). First, the hand net that contained the fish was kept in the tank just at the surface of the water for approximately one minute. During this time the fish swam in the net normally. Next, the fish was gently released into the central point of the tank, where it was allowed to swim along the mirrored wall of the octagonal area for 10 minutes. When faced with own its mirror image, males performed aggressive behaviours (displays, dashes, and attempted bites). Above the test apparatus, a video camera (CCD-TR250, Sony) was mounted to record the fishes’ behaviour. Agonistic displays were distinguished from simple shoaling by the presence of specific behaviours such as broadside swimming, dorsal fin erection, and spreading of the opercula. When the fish swam clockwise along the mirrored wall of the tank, it bent its body leftward and displayed the right side of the body (right eye use) and the operculum was towards the mirror; however, in some cases of fast swimming the individual could not assume the adequate pose. The direction of the display (eye use) was then defined as either ‘left display’ or ‘right display’, depending on which side of the body was displayed while swimming counter-clockwise or clockwise, respectively. A series of agonistic display was regarded as single aggressive display. The number of left displays (indicating left-eye preference) and right displays (right-eye preference) was recorded using a video camera. When the fish remained perpendicular to the mirror, the data were not used in the analysis. The number of aggressive displays is more appropriate to assess behavioural laterality than is the duration of swimming clockwise or counter-clockwise, because the duration of swimming is likely to include both the time spent in actual aggressive responses and that spent simply swimming. We calculated a laterality index (LI) using the following formula:

(number of right aggressive displays – number of left aggressive displays) / (number of right aggressive displays + number of left aggressive displays).

We also calculated the mean of the laterality index absolute values to confirm whether the fish showed individual laterality during behavioural responses. Mean absolute indices significantly different from 0 indicated that the fish exhibited individual-level lateral bias [6, 29]. Significant departures from chance (0) were estimated using a one-sample Wilcoxon signed-ranks test.

2.3.Measurement of morphological asymmetries

After the behavioural test, fish were removed from the experimental apparatus and anesthetized using 1/10000 FA-100 (Tanabe Pharmacy, Inc., Tokyo, Japan). The fish were subsequently fixed in a 10% formalin solution for more than two weeks. Bone staining with alizarin red S was performed on the samples for two weeks. The opercula were removed from the body, and the ventral fin was carefully removed under a binocular microscope. These operations were performed in accordance with the Regulation on Animal Experimentation at Kyoto University.

To calculate the asymmetry index (AI) for head incline, we drew two sagittal lines between the parasphenoid and occipital bone and the occipital bone and a three-vertebrae segment of the spine. We then took a digital photograph and measured the angles between the lines using a digital microscope with image analysis software

(VHX-100, Keyence, Osaka, Japan; Fig. 1a). Measurements were taken three times for each individual to reduce observation errors. As measuring the craniovertebral angle of a three-dimensional object is prone to yielding some extreme values, median values were used for the following analysis instead of mean values (in actuality, the measurement errors were small [ANOVA: $F_{2,72} = 148.2$, $p < 0.001$]). Positive angle values were assigned to vertebrae that curved to the right side in the ventral view, and negative values were assigned to vertebrae that curved to the left. Fish with an angle <0 were designated as 'lefty', and those with an angle >0 were designated as 'righty' (see [25]).

Individual opercular area measurements were taken directly from photos using Image J version 1.42 (US National Institutes of Health, Bethesda, MD, USA; Fig. 1b). The asymmetry index (AI) of opercula was computed for each fish using the following formula:

$$(R - L) / (R + L) \times 100,$$

where R and L are the measured values for right and left opercular areas, respectively. Frequency distribution characteristics of the two AIs were examined using a Watson test, Shapiro–Wilk test, and Bonett–Seier test for Geary kurtosis.

2.4. Correlation between lateral displays and morphological asymmetry

To assess morphological asymmetries that affect lateral bias during aggressive displays (eye use) in each individual, a generalized linear mixed model (GLMM) analysis was performed. The dependent variable was the direction of the aggressive display (left or right side), and the independent variables were morphological traits (craniovertebral angle and/or AI of the operculum) as a fixed effect and the individual as a random effect.

The GLMM analysis, Watson test, and Bonett–Seier test for Geary kurtosis were performed using R version 2.7.0 [22], and the other statistical analyses were performed using JMP version 5 (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1.Aggressive behaviours

The average number of aggressive displays observed per 10 minutes was 58.2 ± 41.2 (mean ± SD). The mean LI for aggressive displays did not differ significantly from zero, indicating no overall tendency towards either left or right bias (mean ± SD = 0.078 ± 0.473; one-sample Wilcoxon signed-ranks test: $T = 31.50$, $p = 0.408$). The mean absolute value of LI differed significantly from zero (one-sample Wilcoxon signed-ranks test: $T = 162.50$, $p < 0.001$), which suggests that individual fish are significantly lateralized with respect to agonistic displays (eye use preference). In other words, individual fish tended to show a bias for either leftward or rightward displays; 13 of 25 fish had a significant bias (five fish showed left bias and eight fish showed right bias; binomial test: $p < 0.05$; Fig. 2). A 1000-times simulation, in which 25 fish randomly displayed 58 times each, showed that the average number of individuals with a significant bias was 1.21 fish (SD = 1.04, binomial test: $p < 0.05$). Therefore, the observed values are higher than those expected from a population in which every fish behaves in an unbiased way relative to a normal distribution.

3.2. *Morphological asymmetry of head inclines*

The mean craniovertebral angle was approximately 0 (mean ± SD = 0.638 ± 2.299°; one-sample Wilcoxon signed-ranks test: T = 41.00, $p = 0.279$). The frequency distribution of the angle strongly deviated from normal (Watson test; $p < 0.01$), and the Geary's kurtosis value was significantly higher than 0.798, which is the value of a normal distribution ($\tau/\sigma = 0.886$, Bonett–Seier test: $p = 0.040$), indicating a clearly bimodal distribution (Fig. 3a). Therefore, the craniovertebral angle was identified as antisymmetry, following the definition of Palmer [26].

The bodies of all sampled fish showed subtle bending to either the left side (C-shaped body) or right side. The craniovertebral angles of nine fish were negative (lefty), and those of the remaining 16 fish were positive (righty) [25].

3.3. Morphological asymmetry of the opercula

The mean opercular area was 13.10 mm^2 (± 1.31, SD). As the mean absolute lateral difference (|right area – left area|) of each individual was 0.32 mm^2 (± 0.21, SD), opercula on the left and right sides were similar in size (mean ± SD, 2.48 ± 1.78% size asymmetry). The mean AI of the opercula was approximately 0 (–0.402 ± 1.483; one-sample Wilcoxon signed-ranks test: $T = -52.50$, $p = 0.162$). The frequency distribution of the AI was normal (Shapiro–Wilk test: $w = 0.978$, $p = 0.845$) and its Geary's kurtosis value did not differ from a normal distribution ($\tau/\sigma = 0.797$, Bonett-Seier test: $p = 0.980$, Fig. 3b). Therefore, opercular area was identified as showing fluctuating asymmetry [26].

A positive correlation between the craniovertebral angle and the AI of the opercula was observed ($R^2 = 0.46$, $F_{1,24} = 19.89$, $p < 0.001$, Fig. 3c). Therefore, fish with greater left curvature tended to have larger left opercula, whereas fish with greater right curvature tended to have larger right opercula. However, the direction of the craniovertebral angle was not completely consistent with the side containing the larger operculum (eight fish were mismatched).

3.4.Factors affecting behavioural laterality

We assessed whether bias in behavioural laterality was affected by two morphological asymmetries using a GLMM analysis. Because of the significant correlation between the craniovertebral angle and the AI of the operculum, we used three models in the analysis: model 1, independent variable = the craniovertebral angle; model 2, independent variable = the AI of the operculum; model 3, independent variable = the craniovertebral angle plus the AI of the operculum. Model 3 was performed to evaluate the effect of the either one morphological factor incorporating the effect of another. In model 1, the craniovertebral angle had a significant effect on behavioural laterality (Table 1). In contrast, the AI of the operculum showed no significant effects in model 2. In model 3, only the craniovertebral angle showed a significant effect. The coefficients of the craniovertebral angle in models 1 and 3 were negative, indicating that lefties displayed mainly with the left side and preferred left eye use in response to the mirror, whereas righties displayed mainly the right side and preferred right eye use. Thus, a lateral difference in the craniovertebral angle is a suitable predictor of behavioural laterality of aggressive displays. However, we found no significant correlation between the magnitude of the LI during aggressive displays and that of the craniovertebral angle (lefties, $F_{1,7} = 1.28$, $p = 0.296$; righties, $F_{1,14} = 0.01$, $p = 0.917$).

4. Discussion

Each *Betta splendens* male exhibited a preference for either the left or right side during aggressive displays in response to its own mirror image. This individual lateralization in eye use is consistent with results from previous studies [4, 6]. Cantalupo et al. [4] found that in male betta, the direction and degree of laterality in eye use during aggressive displays observed in the first test was consistent with that of second test performed two months later. Thus, behavioural laterality in social displays of this fish is individually determined. These results suggest that the behavioural laterality of each fish is determined by some internal and/or external factor. One explanation is that the direction of the hemisphere controlling agonistic responses differs in each individual [4, 6].

Over the last two decades, evidence has accumulated of neuroanatomical asymmetry in various vertebrates (reviewed in [36]) and invertebrates (e.g., [28]), including a nematode [42]. Genetic model organisms allow for the comprehensive study of behavioural laterality [7]. For example, recent work in zebrafish has revealed the genetic mechanisms that control the development of neuroanatomical asymmetries (reviewed in [15]). Even though behavioural laterality during aggressive responses has been identified in numerous organisms, the regions of the brain controlling the behaviour and whether differences in directionality exist between hemispheres remain unclear. Aggression consists of complex cognitive behaviours, including visual scanning, assessment of the opponent, fin erection, dashing, etc. Therefore, the neural mechanisms underlying aggression may be complex.

Some studies have demonstrated a correlation between the direction of behavioural laterality and visceral inversion [1, 12]. The *fsi* strain of zebrafish, which show reversed anatomical morphologies of the viscera and brain (diencephalon), showed a lateralization bias opposite that of wild-type individuals in two behavioural tests, i.e., eye use during a mirror test and a target approach test [1]. Individual laterality in behavioural responses is widely observed among many fish (e.g., [2, 16, 23, 29, 45, 48], but the actual frequency of visceral inversion is very low in wild-type individuals, e.g., in medaka (0.35%, [17]) and zebrafish (from about 5%, [27]). This evidence suggests that brain asymmetries based on visceral inversion cannot explain most cases of individual laterality. In contrast to previous hypotheses that stated one mechanism is responsible for lateralization of the diencephalon, Barth et al. [1] introduced the concept that different neuronal mechanisms underlying functional lateralization may exist. Our understanding of the linkage between behavioural laterality and brain asymmetry is rudimentary, and research employing several different approaches involving external morphology may provide important information about this relationship.

In the present study, more than half of all *B. splendens* exhibited different degrees of left and right bias during aggressive displays. Some researchers have argued that behavioural laterality has biological advantages. For example, McGrew & Marchant [24] reported that wild chimpanzees that showed stronger handedness were more efficient at fishing for termites than were those that showed incomplete handedness. In addition, lateralized fish performed better than non-lateralized fish in escaping predators while capturing prey because they specialize in monitoring predators mainly with one eye while following prey with the other eye [8]. In another study, lateralized female topminnow showed an enhanced ability to attend to different subjects, finding food, and avoiding harassing males [9]. Two other studies have confirmed the benefits of lateralization in fish. Specifically, lateralized fish were found to school with greater cohesion and coordination and to learn to re-orient themselves in a small space more quickly using geometric and non-geometric cues from the environment [3, 41]. In the case of aggressive responses in *B. splendens*, we suggest that fish with pronounced laterality in aggressive displays may conquer an opponent more frequently as compared with fish that show weak laterality. Under these conditions, the strong advantage of lateralization would predict selection against less lateralized individuals. Further investigation is required to evaluate the relationship between the degree of behavioural laterality and win–loss ratios.

No correlation was found between lateral differences in the operculum and the direction of aggressive behavioural bias, indicating that the best-side hypothesis is not supported. Because the left-right differences in opercula were small (2.48 ± 1.78% size asymmetry), betta may not be able to discriminate the morphological asymmetry of opercula. Even some birds may not discriminate such size asymmetry. For instance, starlings are required discriminate asymmetries at least 10% different in size [43]. Gross et al. [13] found that male guppies show the brighter sides of their bodies towards live females, but they do not show any lateral display bias towards a non-living model female. These types of environmental conditions may partially explain the present results.

Our results clearly indicate that lateralized eye use during aggressive displays is correlated with asymmetry in head incline. Lefty and righty morphs show mainly left- and right-biased eye use during displays, respectively; however, three fish showed mismatched directions (with significant bias) between the head incline angle and aggressive displays (Fig. 2). Further examinations are necessary to determine whether this mismatch is due to the presence of individuals with a major trend reversal or is an experimental artefact. Previous studies have revealed that laterality in foraging behaviours correlates with morphological asymmetry [18, 25, 45]. Takahashi and Hori [44] found that asymmetric mouth morphology is associated with mating tactics in scale-eating cichlids, which exhibit reproductive pairings between lefties and righties (i.e., disassortative mating). These data suggest that left-right biases in various behaviours correspond to morphological asymmetries. In aquatic systems, lateralized behaviour may play a role in individual fitness [46]. Thus far, the reason for the relationship between behavioural laterality of aggressive displays and morphological asymmetry is not clear; however, a variety of lateralized behaviours must depend on some internal factors, such as the brain and/or motor bias. Morphological asymmetries of the mouth and of head incline appear to be an appropriate external indicator of a lateralized internal factor. Such morphological asymmetry is potentially useful for studying the association between cerebral lateralization and individual laterality of behaviour. Therefore, it is necessary to re-examine the widespread behavioural laterality in fish from the perspective of morphological asymmetry.

Acknowledgements

We are grateful to M. Yasugi, S. Tobo and other members of the Laboratory of Animal Ecology, Graduate School of Science, Kyoto University for their valuable and critical comments on the early draft. This study was partly supported by Scientific Research on Priority Areas (19570020 and 21370010) and the Global Center of Excellence Program "Formation of a Strategic Base for Biodiversity and Evolutionary Research: from Genome to Ecosystem", from Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

References

[1] Barth KA, Miklosi A, Watkins J, Bianco IH, Wilson SW, Andrew RJ. fsi zebrafish show concordant reversal of laterality of viscera, neuroanatomy, and a subset of behavioral responses. Curr Biol, 2005; 15: 844–850.

[2] Bisazza A, Cantalupo C, Vallortigara G. Lateral asymmetries during escape behavior in species of teleost fish (*Jenynsia lineata*). Physiol Behav, 1997; 61: 31-35.

[3] Bisazza A, Rogers LJ, Vallortigara G. The origins of cerebral asymmetry: a review of behavioural and brain lateralization in fishes, reptiles and amphibians. Neurosci BioBehav R, 1998; 22: 411-426.

[4] Cantalupo C, Bisazza A, Vallortigara G. Lateralization of displays during aggressive and courtship behaviour in the siamese fighting fish (*Betta splendens*). Physiol Behav, 1996; 60: 249-252.

[5] Casperd LM, Dunbar RIM. Asymmetries in the visual processing of emotional cues during agonistic interactions by gelada baboons. Behav Process 1996; 37: 57–65.

[6] Clotfelter ED, Kuperberg ES. Cerebral lateralization and its relationship to phylogeny and aggression in anabantoid fishes. Brain Behav Evolut, 2007; 69: 169-175.

[7] Concha ML. The dorsal diencephalic conduction system of zebrafish as a model of

vertebrate brain lateralisation. Neuroreport, 2004; 15: 1843–1846.

[8] Dadda M, Bisazza A. Does brain asymmetry allow efficient performance of simultaneous tasks? Anim Behav, 2006; 72: 523-529.

[9] Dadda M, Bisazza A. Lateralized female topminnows can forage and attend to a harassing male simultaneously. Behav Ecol, 2006; 17: 358–363.

[10] Deckel AW. Laterality of aggressive responses in *Anolis* . J Exp Zool, 1995; 272: 194–200.

[11] Denenberg VH. Hemispheric laterality in animals and the effects of early experience. Behav Brain Sci, 1981; 4: 1-21.

[12] Facchin L, Burgess HA, Siddiqi M, Granato M, Halpern ME. Determining the function of zebrafish epithalamic asymmetry. Philos T Roy Soc B, 2009; 364: 1021-1032.

[13] Gross, M.R., Suk, H.Y., & Robertson, C.T. Courtship and genetic quality: asymmetric males show their best side. P Roy Soc lond B Bio, 2007; 274: 2115-2122.

[14] Güntürkün O, Diekamp B, Manns M, Nottelmann F, Prior H, Schwarz A, Skiba M. Asymmetry pays: visual lateralization improves discrimination success in pigeons. Curr Biol, 2000; 10: 1079-1081.

[15] Halpern ME, Liang JO, Gamse JT. Leaning to the left: laterality in the zebrafish forebrain. Trends Neurosci, 2003; 26: 308–313.

[16] Heuts BA. Lateralization of trunk muscle volume, and lateralization of swimming turns of fish responding to external stimuli. Behav Process, 1999; 47(2): 113-124.

[17] Hojo M, Takashima S, Kobayashi D, Sumeragi A, Shimada A, Tsukahara T, Yokoi H, Narita T, Jindo T, Kage T, Kitagawa T, Kimura T, Sekimizu K, Miyake A, Setiamarga D, Murakami R, Tsuda S, Ooki S, Kakihara K, Naruse K, Takeda H. Right-elevated expression of charon is regulated by fluid flow in medaka Kupffer's vesicle. Dev Growth Differ, 2007; 49: 395-405.

[18] Hori M. Frequency-dependent natural-selection in the handedness of scale-eating cichlid fish. Science, 1993; 260(5105): 216-219.

[19] Hori M. Tanganiikako no gyoruigunsyu to sayuusei no doutai (Dynamics of fish communities and laterality in Lake Tanganyika). In: Seitai to kankyo (Ecology and Environment) (Ed. by T. Matsumoto, M. Hasegawa), Tokyo: Baihukan Press, 2007, 51-95.

[20] Hori M, Ochi H, Kohda M. Inheritance Pattern of Lateral Dimorphism in Two Cichlids (a Scale Eater, *Perissodus microlepis*, and an Herbivore, *Neolamprologus moorii*) in Lake Tanganyika. Zool Sci, 2007; 24(5): 486-492.

[21] Hunt GR, Corballis MC, Gray RD. Design complexity and strength of laterality are correlated in New Caledonian crows' pandanus tool manufacture. Proc R Soc Lond B, 2006; 273: 1127–1133.

[22] Ihaka R, Gentleman R. R: a language for data analysis and graphics. J Comput Graph Stat, 1996; 5: 299-314.

[23] Izvekov E, Chebotareva Y, Izyumov Y, Nepomnyashchikh V, Medyantseva E. Behavioral and morphological asymmetries in roach Rutilus rutilus (Cyprinidae: Cypriniformes) underyearlings. J Ichthyol, 2009; 49: 88-95.

[24] McGrew WC, Marchant LF. Laterality of hand use pays off in foraging success for wild chimpanzees. Primates, 1999; 40: 509-513.

[25] Nakajima, M., Yoda, T., Katano, O. Righty fish are hooked on the right side of their mouths - observations from an angling experiment with largemouth bass, *Micropterus salmoides*. Zool Sci, 2007; 24: 855-859.

[26] Palmer AR. Fluctuating asymmetry analysis: a primer. In: Developmental Instability: Its origins and evolutionary implications. (ed. Markow T. A.) Netherlands: Kluwer Academic Publishers. 1994, 335-364.

[27] Palmer AR. Symmetry breaking and the evolution of development. Science, 2004; 306: 828-833.

[28] Pascual A, Huang KL, Neveu J, Preat T. Neuroanatomy: brain asymmetry and long-term memory. Nature, 2004; 427: 605–606.

[29] Reddon AR, Gutiérrez-Ibáñez C, Wylie DR, Hurd PL. The relationship between growth, brain asymmetry and behavioural lateralization in a cichlid fish. Behav Brain Res, 2009; 201: 223–228.

[30] Robins A, Lippolis G, Bisazza A, Vallortigara G, Rogers LJ. Lateralized agonistic responses and hindlimb use in toads. Anim Behav 1998; 56: 875–881.

[31] Rogers LJ. Laterality in animals. International Journal of Comparative Psychology, 1989; 3: 5-25.

[32] Rogers LJ. Evolution of hemispheric specialization: advantages and disadvantages. Brain Lang, 2000; 73: 236-253.

[33] Rogers LJ. Lateralization in vertebrates: its early evolution, general pattern, and development. Adv Study Behav 2001; 31: 107–161.

[34] Rogers LJ. Lateralization in Vertebrates: Its Early Evolution, General Pattern and Development, in Advances in the Study of Behavior, Ed. by P. J. B. Slater, J. Rosenblatt, C. Snowdon, and T. Roper, 2002, 31: 107–162.

[35] Rogers LJ, Zucca P, Vallortigara G. Advantages of having a lateralized brain. Proc R Soc Lond B, 2004; 271:S420–S422.

[36] Rogers LJ, Andrew RJ. Comparative vertebrate lateralization. Cambridge,UK: CambridgeUniversity Press, 2002.

[37] Rogers LJ, Zappia JV, Bullock SP. Testosterone and eye–brain asymmetry for copulation in chickens. Experientia 1985; 41: 1447–1449.

[38] Seki S, Kohda M, Hori M. Asymmetry of mouth morph of a freshwater goby, *Rhinogobius flumineus*. Zool Sci, 2000; 17(9): 1321-1325.

[40] Simpson MJA. The display of the Siamese fighting fish, *Betta splendens*. Anim Behav Monogr, 1968; 1: 1–73.

[41] Sovrano VA, Bisazza A, Vallortigara G. Animals' use of landmarks and metric information to reorient: effects of the size of the experimental space. Cognition, 2005; 97: 121-133.

[42] Suzuki H, Thiele TR, Faumont S, Ezcurra M, Lockery SR, Schafer WR. Functional asymmetry in Caenorhabditis elegans taste neurons and its computational role in chemotaxis. Nature, 2008; 454: 114-116.

[43] Swaddle JP, Johnson CW. European starlings are capable of discriminating subtle size asymmetries in paired stimuli. J Exp Anal Behav, 2007; 87: 39-49.

[44] Takahashi T, Hori M. Evidence of disassortative mating in a Tanganyikan cichlid fish and its role in the maintenance of intrapopulation dimorphism Biol Lett,

2008; 4: 497-499.

[45] Takeuchi Y, Hori M. Behavioural laterality in the shrimp-eating cichlid fish *Neolamprologus fasciatus* in Lake Tanganyika. Anim Behav, 2008; 75 : 1359-1366.

[46] Takeuchi Y, Tobo S, Hori M. Morphological asymmetry of the abdomen and behavioral laterality in atyid shrimps. Zool Sci, 2008; 25: 355-363.

[47] Vallortigara G. Comparative neuropsychology of the dual brain: a stroll through animals' left and right perceptual worlds. Brain Lang, 2000; 73: 189-219.

[48] Vallortigara G, Bisazza A. How ancient is brain lateralization? In: Comparative vertebrate lateralization (ed. L. J. Rogers & R. J. Andrew), Cambridge, UK: Cambridge University Press, 2002. 9-69.

[49] Vallortigara G, Rogers L. Survival with an asymmetrical brain: Advantages and disadvantages of cerebral lateralization. Behav Brain Sci, 2005; 28: 575-633.

[50] Vallortigara G, Rogers LJ, Bisazza A. Possible evolutionary origins of cognitive brain lateralization. Brain Res Brain Res Rev, 1999; 30: 164-75.

[51] Vanegas H, Ito H. Morphological aspects of the teleostean visual system: a review. Brain Res Rev 1983; 6: 117–37.

Table 1.

Results of GLMM analysis on the LI of aggressive displays in *Betta splendens*.

Model	Variable	Coefficient	SE	*z*	*p*	
Model 1	Craniovertebral angle	−0.191	0.088	−2.182	0.029	*
Model 2	AI of opercula	−0.050	0.149	−0.333	0.739	
Model 3	Craniovertebral angle	−0.321	0.115	−2.783	0.005	*
	AI of opercula	0.300	0.181	1.658	0.097	

Figure legends

Fig. 1 Photographs illustrating (a) the craniovertebral angle of lefty and righty morphs and (b) left and right opercula in *Betta splendens*. The craniovertebral angle is measured from the intersection of two dorsal sagittal lines: one (solid line) runs from the parasphenoid to the occipital bone, and the other (dashed line) runs from the occipital bone to the three-vertebrae spinal segment in the ventral view.

Fig. 2 Percentage of left-side (empty column) and right-side (grey column) displays for all subjects (n = 25). '*L*' and '*R*' under the individual number denote lefty and righty fish, respectively. The asterisks above each column indicate significant lateral bias based on a binomial test ($p < 0.05$).

Fig. 3 Frequency distributions of (a) the craniovertebral angle and (b) the AI of the operculum. The dashed line indicates a normal curve fitted to the data. (c) The linear relationship between the craniovertebral angle and the AI of the opercula ($p < 0.001$).

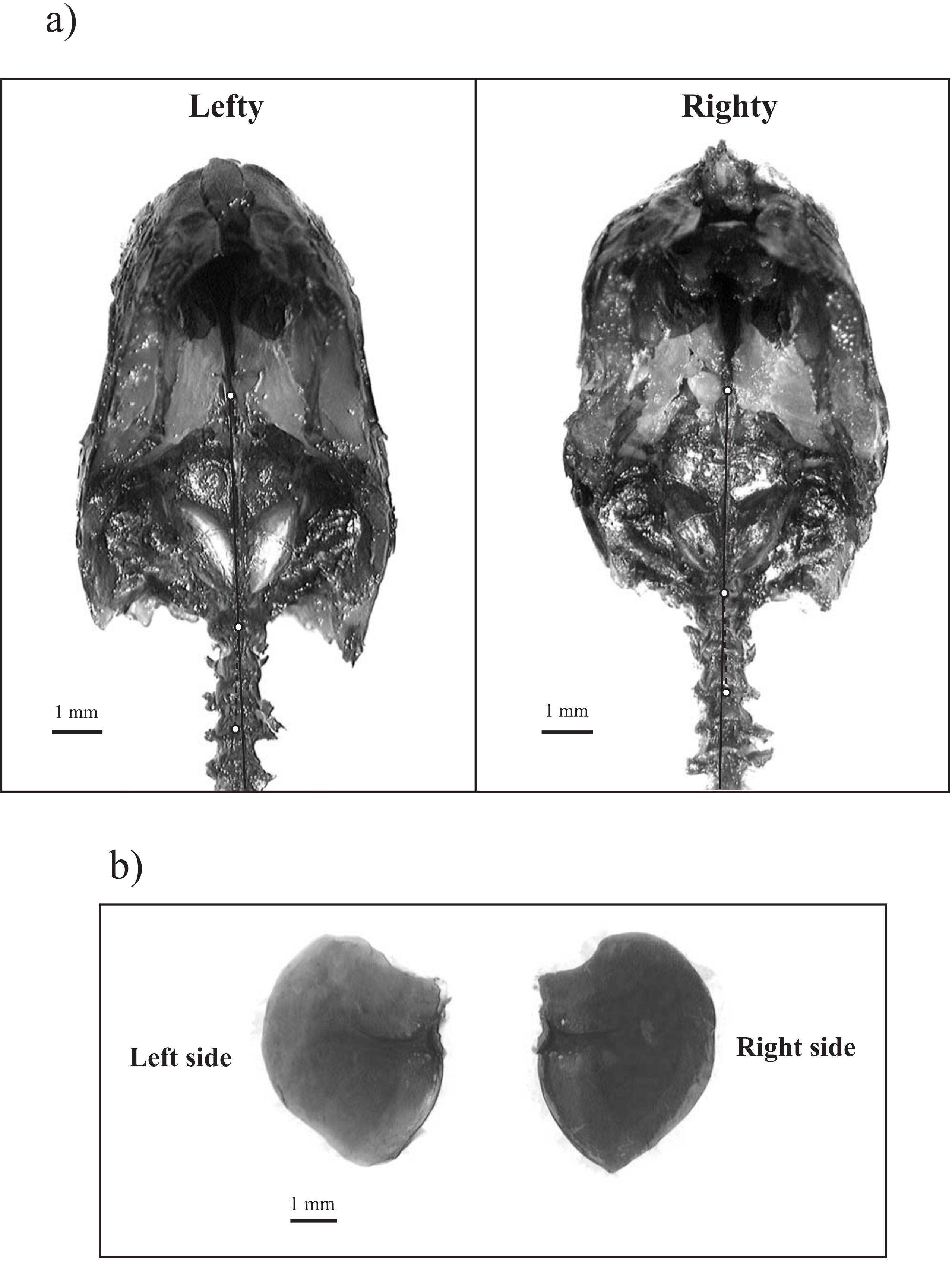

Fig. 1

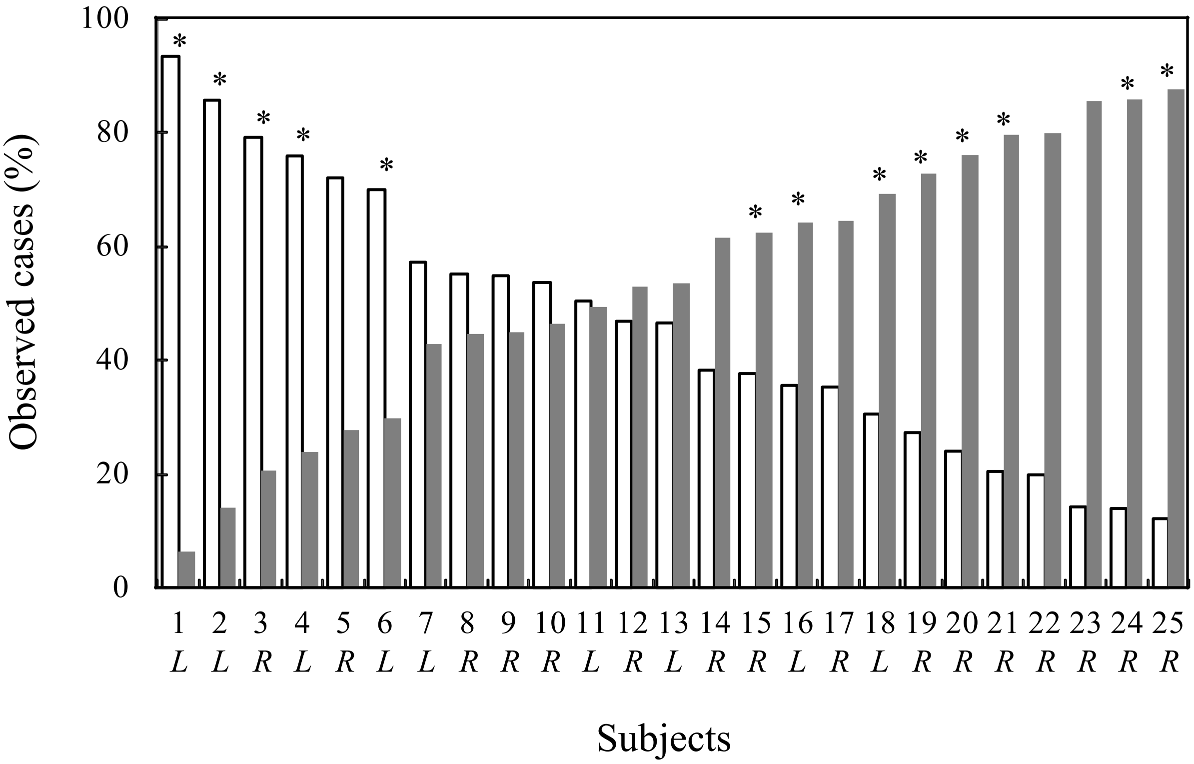
100
80
60
40
20
0
Observed cases (%)
*
1 L
2 L
3 R
4 L
5 R
6 L
7 L
8 R
9 R
10 R
11 L
12 R
13 L
14 R
15 R
16 L
17 R
18 L
19 R
20 R
21 R
22 R
23 R
24 R
25 R
Subjects

Fig. 2

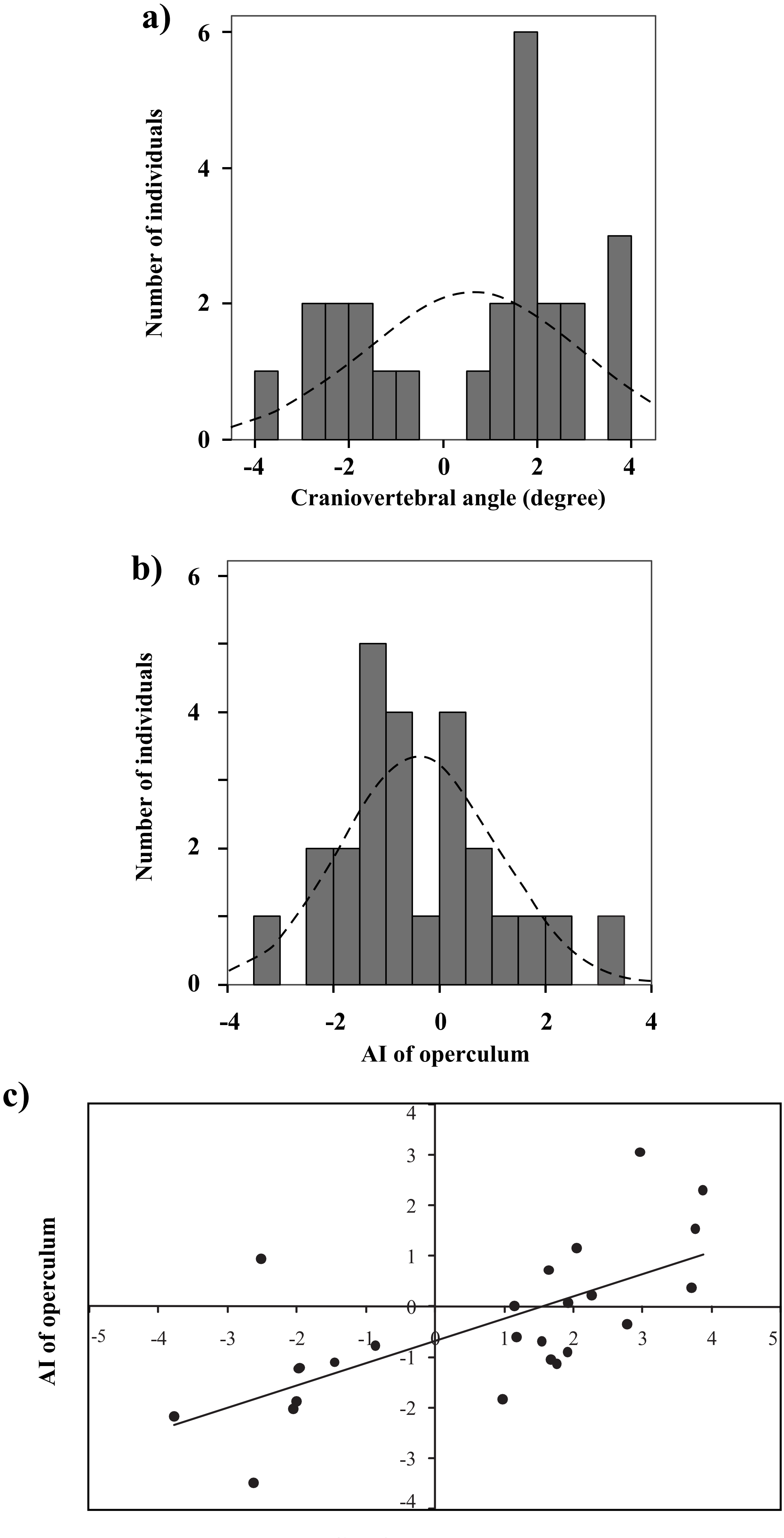
a)
Number of individuals
0
2
4
6
-4
-2
0
2
4
Craniovertebral angle (degree)
b)
Number of individuals
0
2
4
6
-4
-2
0
2
4
AI of operculum
c)
AI of operculum
4
3
2
1
0
-1
-2
-3
-4
-5
-4
-3
-2
-1
0
1
2
3
4
5
Craniovertebral angle

Fig. 3