# Implications of Brain Evolution in Cetaceans and Primates for Highly Intelligent Extraterrestrial Life

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## ABSTRACT

There are stars and Earth-like planets believed to be over 10 billion years in age. "Water worlds" and moons that contain salty oceans may be commonplace in this galaxy. The evolution of cetaceans and primates may provide some clues as to how intelligent life may have evolved on other planets. The most intelligent species of primate, *Homo sapiens*, has an average brain mass (~1350 g) that is considerably larger than any of the other primates but much smaller than the averages for many cetaceans, which are also believed to be very intelligent. The factors that led a subset of primates rather than the comparatively huge-brained cetaceans to dominate (from a human perspective) our planet are reviewed, including language and tool making capability. If intelligent cetacean-like beings evolved convergently in other worlds in response to aquatic habitats similar to Earth's, they would not be expected to have complex tools and technologies, whereas primate-like beings that may have evolved convergently on other planets that are much older than Earth might have long ago developed technologies that surpass our own.

## 1. Brain Evolution & Extraterrestrial Intelligence

What are some of the environmental and behavioral constraints that may have influenced the evolution of extremely intelligent extraterrestrial beings, assuming that such lifeforms exist? Comparative measures of relative brain size (RBS) in primates and cetaceans (whales, dolphins & porpoises), including encephalization quotients (EQ), are frequently used to support the claim that cetaceans are extremely intelligent. Some scholars go so far as to assert that cetaceans "rank near the top of any list measuring neuroanatomical sophistication, next to great apes, humans, and elephants" (Fox, 2020:1). Below, I analyze mean adult brain and body masses for 58 cetacean and 76 primate species (Table 1) (Boddy et al., 2012; Fox, Muthukrishna, & Shultz, 2017; Manger, 2006) and suggest (1) that the

large RBS of dolphins compared to humans may be due at least partly to an artifact of allometric scaling and (2) that absolute brain size, rather than RBS, might be a better indicator of cognitive abilities in cetaceans and primates.

The most intelligent species of primate, *Homo sapiens*, has a considerably larger average brain mass (~1350 g) than any of the other primates. Human brain size is paltry, however, compared to many cetaceans, with the average brain of the sperm whale (*Physeter macrocephalus*) weighing in at over 7,700 g (Ridgway et al., 2016). Why isn't a whale writing this article instead of a primate or, put another way, what factors led a subset of primates rather than the comparatively huge-brained cetaceans to dominate our planet? This question is not only thought-provoking, but the answer to it could also help identify what may or could have led to evolution of extremely intelligent (i.e., at least at the human level) extraterrestrial beings.

## 2. Brain Growth and Body Mass

RBS is defined here as the ratio between brain mass and body mass (brain mass/body mass). Figure 1A shows the typical ontogenetic brain growth curves for humans and chimpanzees. During the first year of life, brain size increases rapidly, and the rate of brain growth continues to decrease in subsequent years until adult brain size is reached. The human postnatal brain "spurt" is steeper than that of chimpanzees, which is why adult humans end up with brains that are over three times the size of adult chimpanzee brains. As can be seen, the curves plotting RBS against body size for different primate taxa in Fig. 1B are shaped inversely compared to ontogenetic curves. Despite their different positions relative to the vertical axis, the curves for the different taxa are similarly shaped, with humans on top (Falk, 2007b).
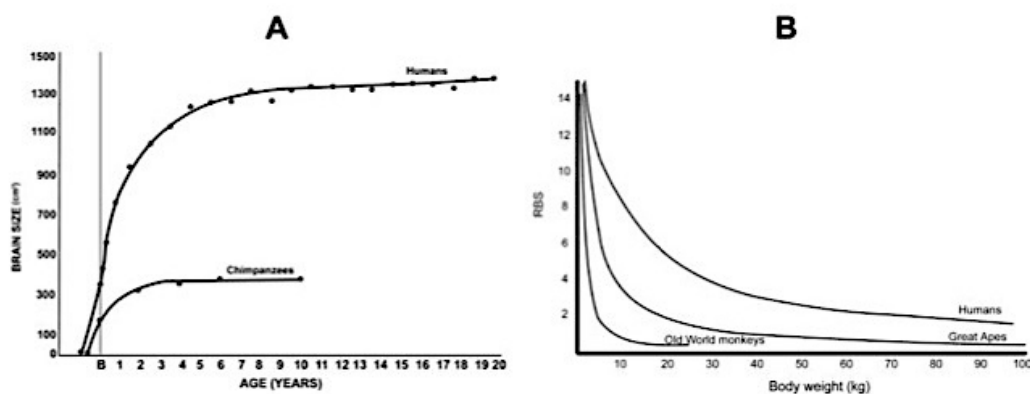


**Figure 1**. *Brain growth and relative brain size in primates. A: Typical ontogenetic brain growth curves for humans and chimpanzees (brain size versus age in years, B = birth). Brain size is in cubic centimeters, a traditional proxy for grams. B: RBS (brain mass/body mass) versus body mass for humans, great apes, and Old World monkeys. See Falk (2007b) for details.*

## Table 1

| Species | Cetaceans, various authors | Brain Mass (g) | Body Mass (g) | RBS | RBS rank cet | Primates, Boddy 2012 | Brain Mass (g)2 | Body Mass (g)3 | RBS | RBS rank prim |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Platanista minor | 164 | 18300 | 0.00896 | | Microcebus murinus | 1.84 | 58.00 | 0.032 | 10 |
| 2 | Neophocaena phocaenoides | 468 | 32400 | 0.01444 | 8 | Tarsius bancanus | 2.70 | 77.60 | 0.035 | 5 |
| 3 | Stenella longirostris | 450 | 33600 | 0.01339 | 10 | Galagoides demidoff | 3.38 | 81.00 | 0.042 | 1 |
| 4 | Neophocaena asiaeorientalis | 422 | 34000 | 0.01241 | 13 | Callithrix pygmaea | 4.64 | 134.75 | 0.034 | 6 |
| 5 | Pontoporia blainvillei | 221 | 34890 | 0.00633 | | Cheirogaleus medius | 3.34 | 179.67 | 0.019 | |
| 6 | Cephalorhynchus hectori | 644 | 38000 | 0.01695 | 2 | Galago senegalensis | 5.90 | 300.33 | 0.020 | |
| 7 | Sotalia fluviatillis | 688 | 42200 | 0.01630 | 4 | Loris tardigradus | 6.00 | 322.00 | 0.019 | |
| 8 | Cephalorhynchus commersonii | 748 | 43667 | 0.01713 | 1 | Saguinus oedipus | 9.64 | 327.14 | 0.029 | 12 |
| 9 | Lagenorhynchus obscuris | 886 | 58470 | 0.01515 | 6 | Callithrix jacchus | 7.73 | 347.45 | 0.022 | |
| 10 | Platanista gangetica | 295 | 59630 | 0.00495 | | Cheirogaleus major | 6.80 | 450.00 | 0.015 | |
| 11 | Stenella coeruleoalba | 884 | 63500 | 0.01392 | 9 | Nycticebus pygmaeus | 7.80 | 480.00 | 0.016 | |
| 12 | Delphinus delphis | 797 | 65087 | 0.01225 | 14 | Leontopithecus rosalia | 13.05 | 512.38 | 0.025 | |
| 13 | Lagenorhynchus albirostris | 1126 | 67500 | 0.01668 | 3 | Saimiri sciureus | 23.35 | 578.70 | 0.040 | 2 |
| 14 | Phocoena spinipinnis | 597 | 68040 | 0.00877 | | Saimiri oerstedii | 22.45 | 605.00 | 0.037 | 4 |
| 15 | Cephalorhynchus heavisidii | 763 | 71000 | 0.01075 | | Saguinus geoffroyi | 14.27 | 634.67 | 0.022 | |
| 16 | Lissodelphis borealis | 1162 | 73000 | 0.01592 | 5 | Nycticebus coucang | 12.74 | 655.50 | 0.019 | |
| 17 | Stenella attenuata | 748 | 77000 | 0.00971 | | Aotus trivirgatus | 16.04 | 701.68 | 0.023 | |
| 18 | Phocoenoides truei | 876 | 78400 | 0.01117 | | Saimiri boliviensis | 24.06 | 750.00 | 0.032 | 8 |
| 19 | Lipotes vexillifer | 510 | 82000 | 0.00622 | | Callicebus moloch | 19.00 | 900.00 | 0.021 | |
| 20 | Sousa chinensis | 1247 | 85000 | 0.01467 | 7 | Perodicticus potto | 12.07 | 929.33 | 0.013 | |
| 21 | Stenella clymene | 666 | 86000 | 0.00774 | | Eulemur rubriventer | 24.90 | 1015.00 | 0.025 | |
| 22 | Lagenorhynchus obliquidens | 1137 | 89750 | 0.01267 | 11 | Avahi laniger | 10.49 | 1285.00 | 0.008 | |
| 23 | Inia geoffrensis | 632 | 90830 | 0.00696 | | Pithecia monachus | 35.00 | 1500.00 | 0.023 | |
| 24 | Phocoenoides dalli | 834 | 98333 | 0.00848 | | Eulemur mongoz | 24.03 | 1559.33 | 0.015 | |
| 25 | Lagenorhynchus acutus | 1200 | 120000 | 0.01000 | | Cebus albifrons | 62.95 | 1620.00 | 0.039 | 3 |
| 26 | Steno bredanensis | 1542 | 123830 | 0.01245 | 12 | Macaca sinica | 58.15 | 1970.00 | 0.030 | 11 |
| 27 | Lagenodelphis hosei | 1103 | 124700 | 0.00885 | | Eulemur macaco | 22.60 | 2086.17 | 0.011 | |
| 28 | Feresa attenuata | 1030 | 125000 | 0.00824 | | Lemur catta | 21.63 | 2090.00 | 0.010 | |
| 29 | Phocoena phocoena | 1735 | 142430 | 0.01218 | 15 | Cebus capucinus | 70.14 | 2104.88 | 0.033 | 7 |
| 30 | Kogia simus | 622 | 168500 | 0.00369 | | Cebus apella | 71.30 | 2589.00 | 0.028 | 14 |
| 31 | Tursiops truncatus | 1573 | 170480 | 0.00923 | | Cebus olivaceus | 72.50 | 2684.50 | 0.027 | 15 |
| 32 | Peponocephala electra | 1392 | 206638 | 0.00674 | | Varecia variegata | 31.20 | 2705.50 | 0.012 | |
| 33 | Kogia breviceps | 1012 | 305000 | 0.00332 | | Daubentonia madagascariensis | 45.15 | 2800.00 | 0.016 | |
| 34 | Grampus griseus | 2387 | 328000 | 0.00728 | | Alouatta seniculus | 45.50 | 2827.50 | 0.016 | |
| 35 | Delphinapterus leucas | 1921 | 498250 | 0.00386 | | Cercopithecus mona | 67.00 | 3001.00 | 0.022 | |
| 36 | Hyperoodon planifrons | 2994 | 600000 | 0.00499 | | Macaca fascicularis | 66.93 | 3109.45 | 0.022 | |
| 37 | Mesoplodon bidens | 1440 | 649000 | 0.00222 | | Ateles paniscus | 108.96 | 3430.00 | 0.032 | 9 |

| # | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 38 | Mesoplodon europas | 2149 | 732500 | 0.00293 | Macaca nigra | 97.50 | 3452.00 | 0.028 |
| 39 | Mesoplodon densirostris | 1463 | 767000 | 0.00191 | Chlorocebus aethiops | 64.13 | 3452.67 | 0.019 |
| 40 | Globicephala macrorhynchus | 4166 | 900770 | 0.00462 | Propithecus verreauxi | 26.70 | 3480.00 | 0.008 |
| 41 | Mesoplodon mirus | 2355 | 929500 | 0.00253 | Cercopithecus cephus | 76.00 | 3508.33 | 0.022 |
| 42 | Globicephala melas | 2893 | 943200 | 0.00307 | Macaca assamensis | 90.50 | 3655.00 | 0.025 |
| 43 | Mesoplodon carlhubbsi | 1860 | 1168000 | 0.00159 | Lagothrix lagotricha | 89.35 | 3905.00 | 0.023 |
| 44 | Monodon monoceros | 2997 | 1578330 | 0.00190 | Macaca nemestrina | 110.00 | 4456.00 | 0.025 |
| 45 | Pseudorca crassidens | 4307 | 2000000 | 0.00215 | Macaca mulatta | 87.99 | 4612.78 | 0.019 |
| 46 | Ziphius cavirostris | 2004 | 2273000 | 0.00088 | Cercocebus agilis | 95.30 | 4700.00 | 0.020 |
| 47 | Orcinus orca | 6052 | 3273000 | 0.00185 | Alouatta caraya | 50.70 | 5012.50 | 0.010 |
| 48 | Eubalaena australis | 2750 | 12500000 | 0.00022 | Lophocebus albigena | 96.80 | 5125.00 | 0.019 |
| 49 | Eschrichtius robustus | 4305 | 14329000 | 0.00030 | Hylobates agilis | 88.10 | 5528.75 | 0.016 |
| 50 | Megaptera novaeangliae | 6100 | 30050000 | 0.00020 | Hylobates lar | 93.99 | 5550.00 | 0.017 |
| 51 | Physeter macrocephalus | 8028 | 35833330 | 0.00022 | Ateles geoffroyi | 104.96 | 5774.00 | 0.018 |
| 52 | Balaenoptera borealis | 4900 | 36666667 | 0.00013 | Alouatta palliata | 50.04 | 5952.00 | 0.008 |
| 53 | Physeter catadon | 7818 | 37093000 | 0.00021 | Hylobates muelleri | 95.31 | 5954.88 | 0.016 |
| 54 | Balaenoptera edeni | 3750 | 40000000 | 0.00009 | Indri indri | 38.30 | 6250.00 | 0.006 |
| 55 | Balaenoptera musculus | 3636 | 50904000 | 0.00007 | Cercopithecus mitis | 75.00 | 6300.00 | 0.012 |
| 56 | Eubalaena japonica | 2700 | 60793171 | 0.00004 | Macaca maura | 94.48 | 6846.00 | 0.014 |
| 57 | Balaenoptera physalus | 5100 | 62500000 | 0.00008 | Procolobus badius | 78.00 | 7000.00 | 0.011 |
| 58 | Balaena mysticetus | 2843 | 90000000 | 0.00003 | Semnopithecus entellus | 111.50 | 7010.00 | 0.016 |
| 59 | | | | | Erythrocebus patas | 100.20 | 7376.00 | 0.014 |
| 60 | | | | | Pygathrix nemaeus | 77.00 | 7500.00 | 0.010 |
| 61 | | | | | Macaca arctoides | 100.70 | 7630.00 | 0.013 |
| 62 | | | | | Theropithecus gelada | 130.00 | 7710.00 | 0.017 |
| 63 | | | | | Ateles fusciceps | 113.60 | 9026.50 | 0.013 |
| 64 | | | | | Aotus lemurinus | 113.50 | 9026.50 | 0.013 |
| 65 | | | | | Trachypithecus francoisi | 94.40 | 9100.00 | 0.010 |
| 66 | | | | | Colobus angolensis | 74.40 | 9670.00 | 0.008 |
| 67 | | | | | Colobus guereza | 83.90 | 10281.25 | 0.008 |
| 68 | | | | | Macaca sylvanus | 87.70 | 11200.00 | 0.008 |
| 69 | | | | | Mandrillus sphinx | 159.20 | 11500.00 | 0.014 |
| 70 | | | | | Papio hamadryas | 142.00 | 12020.00 | 0.012 |
| 71 | | | | | Hylobates syndactylus | 134.80 | 12172.00 | 0.011 |
| 72 | | | | | Pan paniscus | 329.70 | 39700.00 | 0.008 |
| 73 | | | | | Pongo pygmaeus | 341.99 | 54229.04 | 0.006 |
| 74 | | | | | Pan troglodytes | 354.81 | 60433.16 | 0.006 |
| 75 | | | | | Homo sapiens | 1250.43 | 65142.86 | 0.019 |
| 76 | | | | | Gorilla gorilla | 454.55 | 120975.00 | 0.004 |

**Legend for Table 1:** *Relative brain size in 58 cetaceans (from Boddy et al. 2012; Manger 2006; Fox et al. 2017) and 76 primate species (from Boddy et al. 2012). The 15 species with the largest RBS (1 = highest rank) occur among the smallest-bodied half of each order.*

These observations are not limited to primates. What is remarkable is that the shape of brain growth curves for individuals is the same as the shapes of the brain growth curves for species. As Harry Jerison notes: "The aspect that intrigues me is that the growth pattern during development of an individual animal generates an equation that is equally useful for describing relationships among adults of different species" (Jerison, 2001: 312). Thus, just as individual apes and humans have larger RBS than more mature (bigger-bodied) individuals in the same species, adults representing smaller-bodied species of primates usually have larger RBS compared to adults of larger-bodied species (Table 1).

But does RBS in cetaceans scale like that of primates? If one includes the largest species of cetaceans, the overall distribution scales in ways that depart from other mammals: "The relationship between brain size and body size in cetaceans is strongly nonlinear even after log-transforming each variable" (Fox et al., 2017: 1704).  As noted long ago, one researcher considered two of the largest cetaceans known at that time, *Megaptera* and *Balaenoptera*, "as unusual, because of an excess amount of fat, so he calculates his rectilinear regression without them. Just at what point one should stop and say, 'From such a body weight on, the animals all have too much inanimate weight to be considered,' I cannot say" (Count, 1947: 1056).  Nonetheless, RBS in the first 47 cetacean species in Table 1 scales in a mammalian-typical inverse curve (see Figure 2). RBS is compared below (Figure 3) in species from the two orders that are of similar body sizes, i.e., those located to the left of *Phocoena phocoena* (*P.p.*) in Figure 2.

Comparisons of RBS in primates and cetaceans are provided here because this variable is more intuitively accessible than are residuals from log-transformed brain size/body size data and less subject to statistical artifacts.  Figure 3 plots mean adult RBS for 76 species of primates and the 29 smallest-bodied cetacean species (up to and including *Phocoena phocoena*) listed in Table 1.  If one excludes *Homo sapiens* (*H.s.*), it is clear that the distribution of RBS for primates is shaped like the inverse brain growth curves for more restricted taxa of primates (Fig. 1B), as expected. Although the one obvious departure from the primate distribution is *H.s.*, 30 of the 76 primate species have a mean RBS that is larger than the .019 RBS of *H.s.* (Table 1). At .040, for example, mean RBS in the common squirrel monkey (*Saimiri sciureus*) exceeds that of H.s.  Nevertheless, H.s. is clearly "encephalized" (i.e., has a RBS that is relatively large *for its body size*) compared not only to squirrel monkeys but to all other primates (see Figure 3).
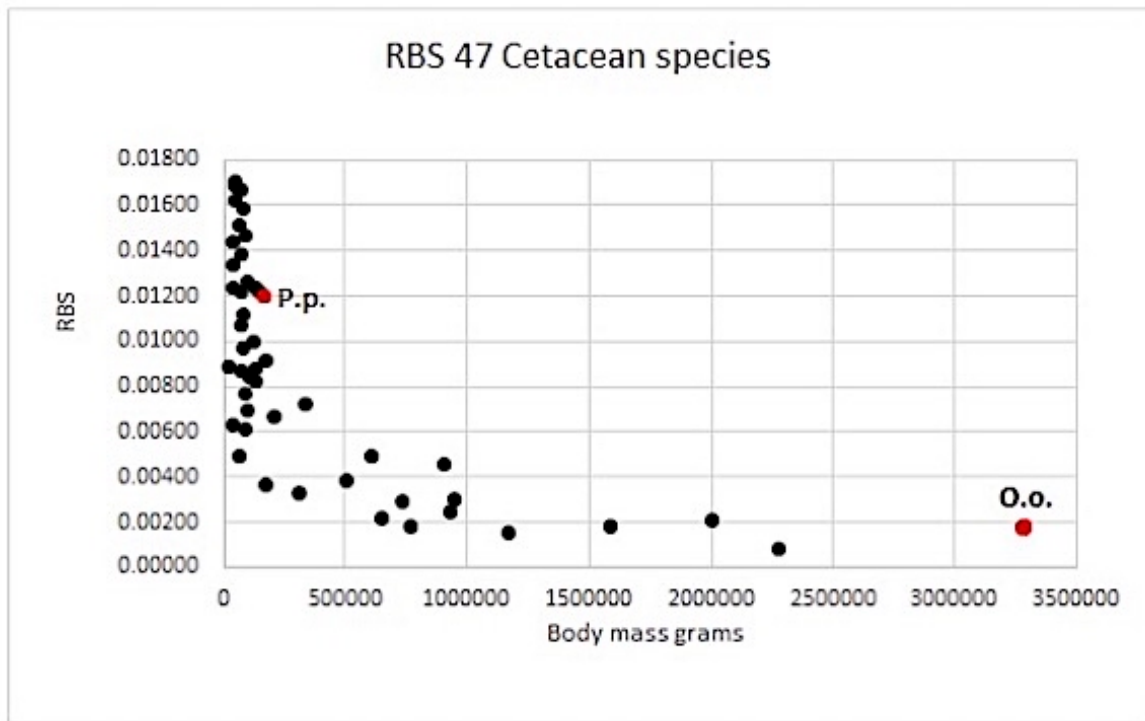
**Figure 2.** *Relative Brain Size (brain mass in grams/body mass in grams) for 47 species of Cetaceans. The largest is Orcinus orca (O.o.). Cetaceans that are smaller than Phocoena phocoena (P.p.) have body masses that overlap with those of great apes and humans (Fig. 3).*
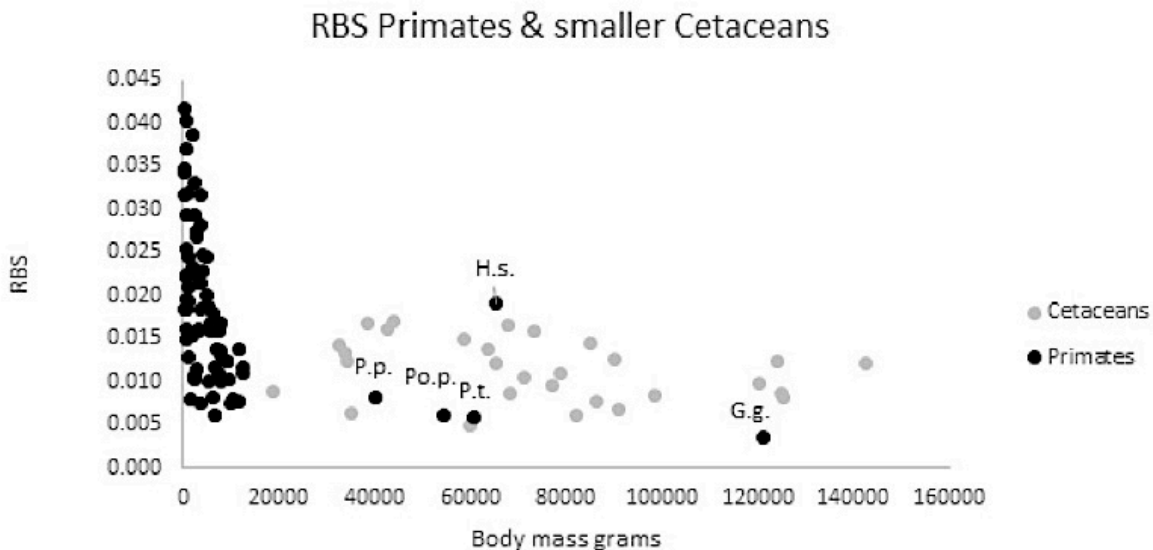


**Figure 3.** *Relative Brain Size (brain mass in grams/body mass in grams) for 76 primate species and 29 cetacean species. The entries represent average adults for each species (Table 1). The largest-bodied cetacean represents Phocoena phocoena. Most of the cetaceans shown here are in the dolphin (Delphinidae) family. Abbreviations of four great apes and human: G.g., Gorilla gorilla; H.s., Homo sapiens; P.p., Pan paniscus; P.t., Pan troglodytes; Po.p., Pongo pygmaeus.*

Because bigger primates tend to have absolutely larger brains but smaller RBS than smaller animals, and despite the fact that they are regarded as more intelligent than monkeys, the four great apes have among the smallest RBS for primates (Figure 3, Table 1). In other words, RBS is smaller in great apes than monkeys because they occupy the bigger-bodied (right) side of the distribution for all primates (Figure 3). Like primates, the cetacean species with the highest RBS are the smaller-bodied ones; the 15 species with the largest RBS (1 = highest) occur among the smallest-bodied half of each order (Table 1). The highest RBS among primates is .042 (*Galagoides demidoff*); the highest among cetaceans is .01713 (*Cephalorhynchus commersonii*). Thirty-eight of the 76 primate species have a RBS that is larger than the largest RBS in any cetacean.

Despite the fact that Figure 3 shows that mean RBS in the smallest cetacean species is more variable and usually greater than the RBS averages for great apes of similar body sizes, one must be careful about interpreting these data with respect to "neuroanatomical sophistication." Unlike *Homo sapiens'* position relative to the primate distribution for RBS, no cetacean species is located far above the general cetacean distribution for RBS. Elsewhere, I have hypothesized that the high RBS in *H.s.* is, indeed, related to neuroanatomical sophistication because of evolutionary and developmental factors associated with the brain spurt that characterizes our species during the first 1-2 years of life (Fig. 1A), when infants are acquiring and developing the distributed neural networks for language (Falk, 2016a, 2016b; Falk & Schofield, 2018). Later in life (and also during hominin evolution), these linguistic networks pave(d) the way for the emergence of other advanced cognitive abilities associated with (among other things) music, mathematics, and reading. The extent of these abilities sets humans apart from all other mammals. It is not just the relative size of the brain (i.e., compared to other primates of approximately similar body sizes) that is associated with neurological sophistication in *H.s.* The brain's wiring is at least as important, and neurological connectivity associated with cognitive processing is beginning to be understood from advanced functional imaging studies of living people. Because imaging of brain physiology in living dolphins (Ridgway et al., 2006) and postmortem computed tomography and postmortem magnetic resonance studies of gross neuroanatomical features of cetacean brains are in their infancy (Kot et al., 2020) functional connectivity related to cognition in cetacean brains remains uncharted territory.

## 3. Dolphins, Water Worlds & Extraterrestrial Intelligence

One approach for exploring the functional implications of high RBS in dolphins might be to

investigate ontogenetic brain growth in the smaller and larger cetaceans and plot the curves separately, as was done for humans and chimpanzees in Fig. 1A. Do the dolphins that are closest to *H.s.* in Figure 3 have a relatively steep rate of postnatal brain growth (brain spurt) compared to other species in their order, as humans do compared to chimpanzees (Fig. 1)? If so, what cognitive and social skills do infant dolphins acquire during the brain spurt, and might any of them (possibly related to audition) require extraordinary neurological processing? Do dolphins have any skills that are as far reaching as the ability of humans to perceive and generate frequencies of little bits of air and use them to understand and generate an infinite number of ideas from/to conspecifics?

No matter how social or self-aware (able to recognize themselves in mirrors, etc.) dolphins may be, and despite comparative cytoarchitectonic and gross neuroanatomical studies of the (*very* differently organized) brains of primates (including humans) and cetaceans, attempts to compare levels of neurological sophistication in dolphins, apes, and humans are, at best, premature (Marino et al., 2008). According to Jerison, the similar RBS of dolphins and humans indicates that their overall information-processing capacity is "about the same. Does this mean that dolphins are as smart as we are? I suppose that depends on what one means by "smart." But it is a nonsense question. It should be obvious that all species use their processing capacity in species-typical ways" (Jerison, 2001: 320). Jerison reasonably suggests that dolphins may be processing unusual amounts of auditory information.

How might these differences relate to extraterrestrial intelligence? In our solar system, in addition to Earth, the moons Enceladus (satellite of Saturn) and Europa (satellite of Jupiter) are believed to have salty oceans, and it is also thought that vast amounts of water may be sequestered beneath the surface of Ganymede (satellite of Jupiter) and that water-ice is beneath the frozen surface of Jupiter's moon, Callisto (Goertzel & Combs 2010; Tyler, 2010). Whether these moons harbor(ed) life is unknown. However, it is estimated that there may be millions of "water worlds" in this galaxy (Goertzel & Combs 2010; Tyler, 2010). If so, and if life evolved in some of them, and depending on other environmental parameters, including temperature, oxygenation, available nutrients, and proximity to the "habitable zone" of their respective suns, one cannot rule out the possibility that some lifeforms may have evolved convergent adaptations in parallel with those of Earth's cetaceans, including high intelligence. This hypothesis awaits future testing, of course.

Body size and absolute brain size are both better predictors of mental capacity and cognitive abilities than RBS in primates (Deaner et al., 2007; Gibson, 2001). As noted, great apes have bigger bodies and bigger brains than monkeys and are generally perceived as more intelligent than the latter,

although RBS is smaller in apes. Could this also be true for cetaceans, in which case cognition in the largest ones, which have the largest brains, might be at least as interesting as that of the smaller-brained dolphins? In any event, the lack of one or more striking outlier for RBS in the cetacean distribution and the large range of variation for cetacean RBS compared to the narrow range for similarly sized great apes suggest that ecological and physiological factors may have been important determinants of the RBS of dolphins.

## 4. Ecological Factors Related to Cetacean Body and Brain Size

Jerison notes "that cetaceans, evolving in a gravitationally odd environment, had different constraints on the size of their bodies than land mammals" (Jerison, 2001:307). Indeed, gravity was relevant for primate and cetacean evolution generally: The smallest-bodied primates live in strictly arboreal habitats; larger-bodied primates shifted to less gravitationally-challenging (i.e., in terms of potentially fatal falls) semi-terrestrial habitats; and the largest hominins eventually shifted to the fulltime ground living that characterizes *Homo sapiens* (Falk, 2000). After the ancestors of cetaceans entered the ocean around 50 million years ago, some of them evolved large increases in body mass (Montgomery et al., 2013), likely in response to relaxed gravitational constraints combined with the availability of sufficient nutrition. Brain mass increased as well. Since most variation in mammalian brain size is 'explained' by body size (Jerison, 1991:54), it is reasonable to speculate that increased body mass was initially targeted by natural selection in some cetaceans and that brain mass went along for the ride. (This would not have excluded cognition and its neurological substrates from also being potential targets to some degree.) Positing body mass as a prime target for natural selection as early cetaceans underwent adaptive radiation is consistent with Bergmann's rule, since increased body mass maximizes body volume relative to surface area, thus facilitating heat retention in cold aquatic habitats. Similarly, cetaceans' globular body shape and lack of long appendages likely promote heat retention (Allen's rule). Significantly, Bergmann's rule is known to apply to the global distribution of cetaceans, since interspecific body size strongly correlates with water temperature, with large-bodied species being favored in colder environments (Torres-Romero, Morales-Castilla, & Olalla-Tárraga, 2016).

A recent analysis (Fox, 2020) dismisses the "thermogenesis hypothesis" that cetacean brains evolved to be large, at least partly, under pressure from water temperature (Manger et al., 2020), and in the process mischaracterizes my radiator theory of hominin brain evolution as a proposition that "the brain served as a radiator to disperse heat," citing another source that incorrectly claims "according to the modern radiator theory the human brain developed starting as a refrigerator of itself" (Falk, 1990; Longo,

1996). Because the high rate of metabolism in large human brains generates excessive heat, the radiator theory (Falk, 2007a) is based on the assumption that, as brains increased in size during hominin evolution, so did their thermolytic cooling needs. The hominin cranial radiator was conjectured to consist of an extensive network of tiny valveless veins that evolved in response to altered hydrostatic pressures that were exerted on blood vessels during selection for bipedalism—a network (not to be confused with the *rete mirabile* of carnivores and ungulates) that was exapted to cool the brain selectively under stressful thermal conditions. Although the concept of selective brain cooling in humans was controversial when I proposed the hominin radiator, its anatomical basis has since been demonstrated and imaged (Zenker & Kubik, 1996; see also Falk 2007a: Fig 4). As detailed elsewhere, the radiator theory does not describe the human brain itself as either a cranial radiator or "refrigerator," as asserted by some. Rather, the radiator is a *vascular network* that is "viewed as an underlying and dynamic mechanism that helped regulate brain temperature and, as such, released thermal constraints that would otherwise have kept brain size in check…The radiator is therefore best viewed as a 'prime releaser'… not a prime mover of human brain evolution (Falk, 2007a)." For natural selection to increase brain size, homeostatic mechanisms that can support the brain's presumably increased metabolic and thermal requirements need to be or become available.

Ridgway speculates that dolphin brains may also have a high rate of metabolism that necessitates a mechanism for cooling: "Cetaceans may have adapted special means for cooling. The entire blood supply of their brains passes through a large rete mirabile in the dorsum of the thorax and then into another rete system…before reaching the cranial vault…Such a configuration is well positioned to provide a counter-current heat exchange mechanism capable of regulating temperature in blood reaching the brain" (Ridgway et al., 2016:254). Cetacean brains have also evolved special features in cortical neurons and glia that increase their ability to generate heat (Manger et al., 2020). Together, these cooling and heating adaptations hypothetically would have kept enlarging cetacean brains within safe temperature ranges via dynamic homeostatic processes that released thermal constraints that might, otherwise, have kept brain size in check. As noted, such physiological adaptations need not be viewed as prime movers of brain size evolution; rather, they may have developed on the coattails of behaviors (whatever they were) that were targeted by natural selection, ultimately, resulting in enlarged bodies and brains in many cetaceans.

Significantly, body size sometimes decreased during cetacean (and primate) evolution, and it is not always clear whether enlarged RBS in extant species is the result of increased brain size or decreased

body size (phyletic dwarfism) (Smaers et al., 2021). Because body size decreased during the evolution of some cetaceans including dolphins (Montgomery et al., 2013), one hesitates to equate cognitively the right-side bigger-bodied (smaller RBS) part of the primate distribution with the left-side (larger RBS) part of the cetacean distribution (Figure 3). In other words, it is not clear to what extent one may, or may not, rule out evolutionary reduction in dolphin body mass as a (non-cognitive) factor in their high RBS compared to the great apes, which experienced an evolutionary increase in body mass.

Like some birds and nonhuman primates, dolphins are, indeed, capable of social learning, imitation, and cultural innovation and transmission of certain behaviors (Rendell & Whitehead, 2001). Nonetheless, the conclusion that it "is certain now" that cetaceans "display cognitive skills surpassing any other animal" warrants close scrutiny (Fox, 2020:3). As others have noted, cetaceans do not have hands and fingers. They rarely use, let alone make, tools, with the fascinating exception of sponge carrying by some individuals. Cetaceans lack rudiments of a material culture, unlike wild great apes that construct tree nests and use and sometimes make tools for extractive foraging.

What are the implications for cetacean-like beings that may have evolved within the depths of the many water worlds in this galaxy? Even if such beings evolved on planets billions of years older than Earth, unless they evolved appendages that were largely dedicated to manipulating material (e.g., similar to human hands), it is reasonable to assume they would have been incapable of making complex tools and would not have developed the technological capability of space flight. This does not preclude the evolution of cognitive capabilities far beyond or quite unlike those of Earth's cetaceans, however.

Regarding the social brain hypothesis to explain the high RBS in dolphins, *many* animals are social and most anthropoid primates including humans are remarkably so. (Highly intelligent orangutans, on the other hand, are relatively solitary.) Interestingly, humans with high-functioning autism (e.g., Asperger syndrome) who famously lack social skills, are known for their analytical, abstract, systematic thinking, which was/is crucial for the cognitive skills that, so far, appear to be unique to people (Falk & Schofield, 2018). There is ample reason to believe that humanity's repertoire of advanced cognitive skills depends largely on neurological substrates that initially evolved in conjunction with the emergence of symbolic grammatical language. Rather than sociality *per se*, an explanation for RBS in some dolphins might best be sought by exploring their whistles and clicks, as Ridgway suggests when comparing *Stenella* and *Steno* (Ridgway et al., 2016:255). And what about the largest-bodied cetaceans that have the absolutely biggest brains on earth? I wonder what's on their minds.

Whatever they think about, whales and the other cetaceans are not building spaceships or texting

on cellphones. Neither, for that matter, are the hundreds of species of nonhuman primates, even though some of them have developed a semblance of material culture. What constrained nonhuman animals from evolving greater intelligence? One way to approach this is to identify the sequence of factors that appear to have been causally, but serendipitously, responsible for the unique 5-7-million-year evolutionary trajectory of hominin cognition: weather changes → reduction of arboreal habitats → shift to terrestrial living → selection for a dominant form of locomotion that happened to free forelimbs → delayed physical maturation of infants → babies' greater dependence on mothers → selection for novel reciprocal mother/infant communications → evolution of these communications, seeding the eventual emergence of language → subsequent independent emergences of mathematics, music, reading, etc., piggybacking on linguistic neurological networks → acceleration in material and technological culture → spacecraft (Falk, 2023 in preparation). Looking at the sequence in reverse, what stands out as the most important are language and, before that, evolving a pair of extremities that had become, more-or-less, dedicated to carrying and making things rather than locomotion.

The medium in which animals live helps explain why cetaceans and nonhuman primates failed to evolve free extremities that became exapted primarily for manipulating material. Cetaceans use their extremities mostly to locomote through water, whereas arboreal and semiterrestrial primates use all four of theirs (five, if they happen to have prehensile tails) mainly to negotiate harder substrates. (Birds, on the other wing, use their forelimbs to navigate through air.) Only the human primate, through several quirks of fate, eventually evolved habitual bipedalism on gravity-friendly terra firma, which led to the evolution of manipulative forelimbs that were "free" to enhance limb-environment-brain interactions. This is why only people have an extensive archaeological record of material culture.

As important as free, manipulative forelimbs were, language was, and is, the biggie. No matter how clever Flipper is or how much an elephant remembers, as far as can be told, on planet Earth only the human primate has evolved full-blown symbolic, grammatical language that may be used to generate and receive an endless stream of ideas. Put that ability with two (or more) manipulative extremities in an environment that has "stuff" and the sky's, literally, the limit.

## 5. Out of This World: Is There Simple and Complex life Elsewhere in the Milky Way?

Attempting to speculate about environmental and behavioral constraints that may have influenced the evolution of extremely intelligent extraterrestrial organisms is, of course, fraught with problems because animals that are known to be highly intelligent (e.g., cetaceans and primates) are all from just one planet. Nonetheless, humans have access to information that is relevant for evaluating the likelihood

that simple life emerged and evolved into more complex forms elsewhere in our galaxy (the Milky Way) as well as the prospect that intelligent life could have emerged and continued to evolve over a long enough time for some extraterrestrial beings to invent broadly successful space travel, which has yet to happen on Earth.

Because the Milky Way is just one grain of sand among many billions of galaxies, confining relevant analyses to data from our own galaxy seems prudent, as is focusing exclusively on data from planets that are more-or-less Earth-like and orbit around suns like ours. Estimates of the number of approximately Earth-sized planets with water and a rocky surface in the habitable zones of G-type stars (like our sun) suggest there could be up to 0.18 potentially habitable planets per G-type star (Kunimoto & Matthews, 2020). Put another way, up to one potentially habitable planet may occur for every ~5.5 G-type stars. One estimate concludes, "Our galaxy has as many as 400 billion stars, with seven percent of them being G-type…[which] means less than six billion stars may have Earth-like planets in our Galaxy" (Matthews quoted by Gough, 2020). Using an estimate of 28 billion G-type stars [7% of 400 billion] and a denominator of 5.5, yields a somewhat more conservative upper limit of approximately five billion potentially habitable planets in just the Milky Way.

Although it is a conservative estimate, five billion potentially habitable planets is a large enough number that it would be hubris to assume that our planet, which is somewhat provincially situated distally in the Orion arm of the Milky Way, is the only one on which life arose or on which intelligent beings eventually evolved. This is especially true if the emergence of simple life on Earth around 3.8 billion years ago occurred via relatively simple and broadly applicable processes. It has recently been hypothesized that life may have originated via the emergence of simple biologically functional peptides that were used for electron transfer, which were likely a factor that contributed to the eventual emergence of "more complicated protein fold assembly facilitated by bound metals…[that] led to the structural diversity we observe today" (Bromberg et al., 2022:9). This explanation entails fewer constraints on the spontaneous emergence of life than suggested by previous research, including the classic spark-discharge experiments that began in the 1950s (Miller, 1953). It, thus, seems reasonable to consider today's more streamlined hypothesis about the spontaneous emergence of simple life as a possible model for other potentially habitable planets.

With respect to the existence of relatively simple extraterrestrial life on one particular planet, Mars, some scientists believe that microbial life that resembled Earthly cyanobacteria, green algae, lichens, fungi, and mat-forming organisms likely proliferated there between 3.0 and 4.2 billion million

years ago, before Mars lost its magnetic field and atmosphere; that fragments or traces of these simple forms became fossilized (Elewa, 2021; Joseph et al. 2020a,c, 2021b) including structures resembling tube worms (Joseph et al. 2021a). Subsequent statistical analyses of photographs of 'tube-like' structures have determined they are similar to fossilized cases from terrestrial tube worms (Armstrong, 2021a). In addition, images of spheroid structures have been interpreted as possible fossilized lichens and fungal puffballs (Armstrong, 2021b) but which others have argued may be hematite (Suamanarathna et al., 2021). Similarly, analyses of photographs of lozenge microstructures "support the evidence that [they] are possible fossils of Martian microalgae" (Bianciardi et al., 2021:70). Some believe that algae and lichens may still be extant and contribute to oxygen production on Mars (Joseph et al. 2020b; Latif et al., 2021). Sequential images of specimens on Mars have also been interpreted as evidence of fungus that is growing (Joseph et al. 2021b).  Recently, carbon signatures measured from powdered rock samples that were collected from the surface of Mars by NASA's rover, Curiosity, have been interpreted as a possible vestige of recent and ancient life because such signatures are associated with biological processes on Earth, but this is just one of several unconventional explanations (House et al., 2022; Shekhtmas, 2022). It is important to keep in mind that, as convincing as they may seem, all of the above hypotheses have yet to be proven and will continue to be tested.

## 6. Dyson Spheres Orbiting Alien Suns?

Things get even more speculative when we turn to possible signs of highly intelligent extraterrestrial life. Although controversial, pervasive unexplained aerial sightings have had enough credibility to cause the Pentagon to recently create a group to study them (Barnes, 2021). The 2015 observation of unusual light curves from a sun-sized star (Boyajian's star) located in the Cygnus constellation (Boyajian et al., 2016) and subsequent discovery of 21 other stars that may be similar (Schmidt, 2019) has led some to support the controversial hypothesis that beings far more advanced than humans may have invented energy-capturing megastructures (sometimes called Dyson spheres) that orbit distant stars (Horvat, 2015,; Joseph & Duvall, 2021; Wright & Sigurdsson, 2016). Despite the fact that many, perhaps most, astronomers think that natural causes are likely to explain the irregular dimming in the light from these stars, NASA recently funded a project that includes exploring the megastructure hypothesis by analyzing data collected by its Transiting Exoplanet Survey Satellite (Oberhaus & Donlin, 2021).

## 7. Postcards from Earth

Earth is around 4.6 billion years old, which is relatively young compared to the approximately

13.6 billion years during which Earth-sized planets have been forming in the Milky Way (Campante et al., 2015:1). This indicates that, having had more time, the development of intelligent life could be much further along on older inhabited planets than it is on Earth. Some think, however, that our species will become extinct (possibly due to weapons of mass destruction) before it has had enough time to achieve widely successful space travel and/or colonize space (Gee, 2021). If this happens (but see below), then we would be down to n=0 examples of known life that could potentially have reached the level of technological achievement necessary to bring long-distance space travel to fruition.

The fossil record of mass extinctions is illuminating because it shows that animals have repeatedly become extinct on Earth for any number of reasons including climate change, geological disruptions from meteorite impacts, and disease, which may have implications for the future of humanity. Remarkably, it is not necessary for an entire species to be eliminated immediately by such events for it to become extinct. Numerous clades of apparently biologically successful species had "lingering demises" after initially appearing to survive mass extinctions (dubbed "dead clade walking," Jablonski, 2001:5395), which may have been due to, among other things, restricted "taxonomic breath" (Jablonski 2001:5396). Consistent with this, Gee argues that partly because humans have become one relatively genetically homogeneous global population, *Homo sapiens* is unlikely to "survive more than another few thousand to tens of thousands of years" (Gee, 2021:188). Gee further suggests that "extinction will still be the fate of humanity, even if one day the species makes it to the stars. The colonies of humans will be very small and separated by vast distances, raising the possibility that many will fail for lack of people and genetic diversity, and those that succeed will, eventually, diverge into different species" (p. 206-207). (As an aside, speciating would not be such a bad thing. After all, *Homo sapiens* branched off [speciated] from *Homo erectus* and changes in the future descendants of *Homo sapiens*, including speciation events, would presumably be adaptive.)

So, what, if anything, does an analysis of intelligent life on Earth suggest about the environmental substrates and physical forms of extraterrestrial life that would, hypothetically, be intelligent enough to engage in space travel? My guess is that (at least a subset of) such beings would have evolved in environmental mediums that had gravitational properties that permitted the emergence of two or more manipulative extremities, and that said environments also had a good supply of potentially useful material. I think ET would be descended from social predecessors that facilitated its evolution of some sort of sophisticated language. As to body shape, number of limbs, digits, etc., these details may well vary with the home planet. Who's to say that it is necessary to have four extremities or five digits at the

end of each one as we humans do? (After all, the pulsating limb of the dying Martian at the end of the 1953 movie *War of the Worlds* only had three.)

As far as we know, *Homo sapiens* speciated (i.e., became a clade) from other hominins around 300,000 years ago (Richter et al., 2017). Even if our species is a "dead clade walking," the few thousand to tens of thousands of years that Gee predicts we have left comprise an enormous amount of time in terms of potential technological evolution because *Homo sapiens* is on an accelerating technological roll (Falk & Schofield, 2018). As discussed above, spoken language probably began to emerge millions of years ago in early ancestors of humans in conjunction with the evolution of distributed neurological networks, which eventually provided substrates for the (much more) recent emergence of other cognitive abilities such as music, math, reading, etc. Reading was a biocultural invention that arose extremely recently—i.e., about 5,500 years ago (originally using a Sumerian script). It not only revolutionized how our species collects, transmits, and remembers information, it also became heritable (i.e., associated with specific genetic substrates) while simultaneously rewiring parts of the human brain. Fast forward to 1993 when computers and the Internet became publicly available (Loh & Kanai, 2015), which began another remarkable and even faster revolution in human technology than that started over 5,000 years ago by the invention of reading. Today, less than thirty years after the Internet became widely available, technology has, again, made another leap by combining information and communication technology, robotics, nanotechnology, and artificial intelligence (AI) with results such as brain-computer interfaces (i.e., merging computers with brains) (Zdravkove, 2019) and the invention of "soft" robots designed from clusters of cells that can replicate and perform work (Kriegman et al., 2021)—so-called living Xenobots. Interestingly, the latter "suggests that future technologies may, with little outside guidance, become more useful as they spread; and that life harbors surprising behaviors just below the surface, waiting to be uncovered" (Kriegman et al., 2021:1).

*Homo sapiens* is not only inventing new technology that is radically changing global human society at a phenomenal pace (Zdravkove, 2019), the gene pool(s) and brains of our species are changing (and will continue to change) in the process, partly in association with rapid epigenetic changes that affect the nervous system and partly as a result of selection for individuals who, although less socially adept than their peers, are technologically savvy, driven, and creative (Falk & Schofield, 2018). The bottom line is we have little clue about the scope of the innovations our species will create in the next half century, but we can be sure some of them will be beyond our wildest current dreams. And if we can't imagine the breath of technology in the near future of the most intelligent species on the one habitable

planet that we know well, how can we comprehend "the mind, purpose, motives or technological and scientific capabilities of intelligent extraterrestrials that may have evolved beyond our current level of ability billions of years ago" (Joseph & Duvall, 2021:141)? Our species may well last long enough to invent long-distance space travel and, if so, who knows what that will bring? Although intelligent life has currently been proven to exist only on Earth, I wouldn't bet against the existence of even more intelligent extraterrestrial beings whose ancestors evolved on substrates and under circumstances that were conducive to the emergence of open-ended complex symbolic communication and the manufacturing of complex material culture.

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