The common octopus, *Octopus vulgaris*, is an active marine predator known for the richness and plasticity of its behavioral repertoire, and remarkable learning and memory capabilities. Octopus and other coleoid cephalopods, cuttlefish and squid, possess the largest nervous system among invertebrates, both for cell counts and body to brain size. *O. vulgaris* has been at the center of a long-tradition of research into diverse aspects of its biology. To leverage research in this iconic species, we generated 270 Gb of genomic sequencing data, complementing those available for the only other sequenced congeneric octopus, *Octopus bimaculoides*. We show that both genomes are similar in size, but display different levels of heterozygosity and repeats. Our data give a first quantitative glimpse into the rate of coding and non-coding regions and support the view that hundreds of novel genes may have arisen independently despite the close phylogenetic distance. We furthermore describe a reference-guided assembly and an open genomic resource (CephRes-gdatabase), opening new avenues in the study of genomic novelties in cephalopods and their biology.

**Background & Summary**

*Octopus vulgaris* is a benthic, neritic species belonging to the class Cephalopoda. It occurs from the coastline to the outer edge of the continental shelf, inhabiting various marine habitats at depths spanning from 0 to 200 m. *O. vulgaris* is one of the most widely distributed species belonging to the genus, and is an important commercially harvested resource for human consumption. It is found worldwide in temperate and tropical waters. Throughout its distribution range, the animal undertakes limited seasonal migrations: mostly found in deep waters in winter and shallow waters in summer.

*O. vulgaris* is perhaps the most famous and best studied of all octopus species, largely due to the initiative of Professor John Z. Young. Since the late 1940s, Young carried out at the Stazione Zoologica Anton Dohrn of Napoli (Italy) a systematic analysis of the neural structures underlying behavioural plasticity in this animal. Based on this contribution, the anatomy of *O. vulgaris* nervous system and its physiology and life history have been well characterized. It is the phenomenological proximity of behavioral traits and phylogenetic distance in respect to higher vertebrates that guaranteed the short, but wide success of cephalopods. *O. vulgaris* in particular became a “model of the brain” and more recently a case for studying the evolution of cognition.
in invertebrates\textsuperscript{7,14–19}. Researchers still use \textit{O. vulgaris} as an organism to study behavioural and neural plasticity including learning and memory recall\textsuperscript{15,19,20}, regeneration\textsuperscript{13–14} and sophisticated cognition\textsuperscript{14–17,25}.

Currently available genomic resources for molluscs are scarce, considering the species abundance and the commercial value of the phylum Mollusca. Publicly available molluscan genomes include a dozen representatives from bivalves, gastropods\textsuperscript{26–43} and to-date only three cephalopods, namely the California two-spot octopus \textit{Octopus bimaculoides}\textsuperscript{44} and, more recently, for \textit{Callistoctopus minor}\textsuperscript{45} and \textit{Euprymna scolopes}\textsuperscript{46}.

Although the first step towards cephalopod genetics was made over 30 years ago\textsuperscript{46}, cephalopod research is only slowly entering the genomics era\textsuperscript{16,47}. Obtaining high quality cephalopod genomes has been impeded due to their large size (e.g., \textit{O. bimaculoides}: 2.7 Gb; Gregory, 2018 - Animal Genome Size Database, \url{http://www.genomizesize.com}), heterozygosity and high abundance of repeat regions\textsuperscript{43,47,48}. However, several collaborative genome projects are currently underway for a variety of cephalopod species such as the nautilus, \textit{Sepia officinalis}, \textit{Idiosepius paradoxus} and \textit{Doryteuthis pealeii}.

Cephalopods arose more than 500 Mya and diverged into over 800 current living species with highly diversified life styles and body plans\textsuperscript{48}. Translocations, duplications, exon shuffling and gene conversions occurred within the cephalopod genome during evolution, which might explain the development of different morphological novelties, such as the prehensile arms, the unique jet propulsion system, the ink sac and sophisticated sensory and neural systems\textsuperscript{46}. The analysis of \textit{O. bimaculoides} genome revealed an extensive expansion of particular gene families, including protocadherins and the C2H2 superfamily of zinc-finger transcription factors\textsuperscript{43}, as well as novel octopus-specific genes expressed in specialized structures such as suckers, skin and brain (for review see also Shigeno et al.\textsuperscript{39}). These genome-level novelties are accompanied by other sophisticated innovations such as extensive RNA editing, particularly in the nervous system cells\textsuperscript{49–52}. Furthermore, partial genome sequencing of several cephalopods revealed that repeat elements, in particular transposable elements, are abundant\textsuperscript{53}. Indeed, the genome of \textit{O. bimaculoides} revealed that over 45% of the genome is comprised of repetitive elements\textsuperscript{43}.

The study of cephalopod biological innovations\textsuperscript{10,18,43,55} is driven by the unique scientific value of these animals for evolutionary genomics, neuroscience and cognition\textsuperscript{7,10,18,25,43,55–58} which continues the heritage of the discovery of the action potential in the squid giant axon, a seminal contribution to neuroscience\textsuperscript{59}. Furthermore, the phylogenetic relationships within the cephalopods have not yet been fully elucidated and biological research would benefit from more cephalopod genomes\textsuperscript{60,61}.

In line with those previous and current efforts, and to promote data sharing among cephalopod researchers\textsuperscript{16,47}, we present the sequence and draft assembly of the common octopus, \textit{Octopus vulgaris}, genome. It is noteworthy to report that the two species (i.e., \textit{O. vulgaris} and \textit{O. bimaculoides}), although both belonging to the same genus, go through a substantially different life cycle since the paralarval stage is absent in \textit{O. bimaculoides}\textsuperscript{62}. Therefore, the two species represent different biological and physiological adaptations among closely related species. The genomic sequencing of both octopus species and our online platform to browse these data will allow for future comparative genomics studies, revealing key genomic innovations and facilitating the discovery of the molecular basis of intricate processes such as learning, regeneration and the evolution of complex brains.

Methods

**Genomic DNA preparation.** An adult male belonging to the species \textit{O. vulgaris} Cuvier, 1797 (450 g body weight) was caught by fishermen from the Bay of Naples in 2011\textsuperscript{1,2} and immediately humanely-killed\textsuperscript{63,64}. Given the high rate of heterozygosity in marine organisms\textsuperscript{60,66}, tissue from a single individual was used to extract the genomic DNA (to avoid contamination, spermatophores were used). Spermatophores in octopus are stored within the Needham’s sac, structure that was dissected following Chapko and coworkers\textsuperscript{67}. Tissue (124 mg) was lysis buffer containing proteinase K (300 \textmu g/ml; Sigma-Aldrich, Saint Louis, Missouri, United States) and RNase A (100 \textmu g; Sigma-Aldrich, Saint Louis, Missouri, United States) and was subsequently precipitated. Genomic DNA was dissolved in TE buffer to reach a final concentration of 1 \textmu g/\textmu l.

**Genome sequencing and quality control.** A total of four genomic DNA libraries (with different insert sizes: 170, 250, 500 and 800 bp) were constructed following the Illumina library preparation protocols. Briefly, to construct the paired-end libraries DNA was fragmented by Adaptive Focused Acoustics technology (Covaris) and tested via gel-electrophotometry, the fragmented DNA combined with End Repair Mix (20 °C for 30 min). After purification, DNA ends were blunted and an A base was added to the 3’ ends. DNA adaptors with a single T-base 3’-end overhang were ligated to the above products. Ligation products were purified on 2% agarose gels to recover the target fragments and were purified from the gels (Qiagen Gel Extraction kit, 28704). Several rounds of PCR amplification with PCR Primer Cocktail and PCR Master Mix were performed to enrich the Adapter-ligated DNA fragments. Then the PCR products selected by running another 2% agarose gel to recover the target fragments and the gel purified (QIAquick Gel Extraction kit, QIAGEN). The final library was quantified by assessing the average molecule length (Agilent 2100 Bioanalyzer), and by Real-Time qRT-PCR. A total of 277 Gb of raw data were generated by Illumina Hiseq 2000 at BGI.

All libraries were sequenced in a paired-end mode with read lengths of 100 bp or 150 bp. Reads were filtered and trimmed (100 bp to 95 bp, 150 bp to 145 bp) using SOAPnuke software (\url{https://github.com/BGI-flexlab/SOAPnuke})\textsuperscript{68} which yielded 250 Gb of data. Low-quality reads, reads with adaptor sequences and duplicated reads were filtered, and if the quality of bases at the head or tail of the reads was low, we directly trimmed them from 100 bp to 95 bp (PE100) or form 150 bp to 145 bp (PE150). The remaining high-quality data were used in the further analysis. \textit{SGA PreQC v0.10.14}\textsuperscript{69} modules were run per library and on the combined libraries to estimate various genome parameters (Table 1 and Table 2).
Draft genome assembly. We applied Assembly By Short Sequencing 2.0.2 (ABySS) for both k-mer sizes that were suggested by SGA PreQC. The quality of assemblies (ABySS kmer41 and ABySS kmer81) was evaluated by QUAST. A summary of various statistics is shown in Table 3. Based on the QUAST analysis the optimal kmer size for the ABySS assembly was estimated to be 81. Since a higher heterozygosity rate of the genome was predicted based on these initial results, the Redundans tool was used to reduce the number of ABySS contigs from the initial assemblies. Redundans reduces contigs by removing highly similar contigs. These highly similar contigs are originally the different alleles of the same genomic position, but are too different for the De Brujin graph method to be assembled into the same contig (too much variation inside one kmer). Redundans collapses and scaffolds these reduced contigs into single genomic locations. Redundans reduced the number of scaffolds of the draft genome over seven (7) times, while improving assembly statistics (see Table 3).

Reference Assisted Scaffolding. Given the availability of a relatively good reference genome of a related species (O. bimaculoides), a reference assisted scaffolding tool was used to optimize the genome. The reduced scaffolds were aligned to the O. bimaculoides genome using blastn of the blast+ toolkit. These alignments were used by chromosomer 0.1.3 (https://github.com/gtamazian/Chromosomer) to scaffold the reduced scaffolds according to the given genome.

Assessment of draft genomes. An assessment of the draft genomes (ABySS, Redundans and chromosomer) was performed by looking for the highly conserved genes using BUSCO. The Metazoa odb9 database was used, supplying 978 orthologs. The number of complete orthologs increased with each improvement of the assembly (Table 3), confirming the gain in assembly quality of the final chromosomer version. The final genome build has over 50% complete BUSCOs, and 10% fragmented BUSCOs (orthologs found, but scattered over multiple scaffolds).

Data Records
The draft genome(s) of O. vulgaris as shown in Table 3 has been made publicly available on the genome browser and data repository of the Association for Cephalopod Research that initiated this work (http://www.cephalopodresearch.org/ceph_gdatab/) in collaboration with the Department of Molecular Evolution and Development, University of Vienna. This web resource is based on the browser originally designed by University of California, Santa Cruz (UCSC) and will be maintained and curated to keep track of all present and upcoming octopus genomes. It includes comparative genomics tracks such as read mapping and whole genome alignment between the two octopus species. Raw reads have also been deposited to the NCBI SRA. The reference-guided assembly has been deposited at GenBank and its original version is also provided in the associated FigShare record (chromosomer.fa) together with its annotation (gene_models.chromosomer.gff), and other assemblies listed in Table 3 (Octopus vulgaris genome assemblies). Table 2 and Table 3 summarize statistics about O. vulgaris genome as deduced from our current sequencing data and Fig. 1 shows the kmer (17mer) distribution determining the overall sequencing depth (Table 1 and 2).

| Library ID          | Insert Size(bp) | Read Length (bp) | Data (Gb) | Sequence Depth (X) |
|---------------------|-----------------|------------------|-----------|--------------------|
| SZAXPI006102-158    | 170             | 100              | 82.15     | 29.34              |
| SZAXPI006612-13     | 250             | 150              | 52.25     | 18.66              |
| SZAXPI005989-166    | 500             | 100              | 62.05     | 22.16              |
| SZAXPI005988-169    | 800             | 100              | 53.59     | 19.14              |
| Total               | —               | —                | 250.04    | 89.30              |

Table 1. Main statistics from O. vulgaris sequencing data.

| K-mer_num | Peak_depth | Genome Size | Used Bases | Used Reads |
|-----------|------------|-------------|------------|------------|
| 212,679,899,304 | 76 | 2,798,419,727 | 249,873,643,000 | 2,324,608,981 |

Table 2. k-mer = 17 raw read statistics for Octopus vulgaris genome data.

|          | # scaffolds | genome size | N50/L50 | N75/L75 | Ns/100 kbp | Complete BUSCOs | Fragmented BUSCOs |
|----------|------------|-------------|---------|---------|------------|-----------------|------------------|
| ABySS k41 scaffolds | 26,350,077 | 3.30 Gb | 1,488 bp | 199,442 | 767 bp | 503,977 | 979.41 | 112 | 50 |
| ABySS k81 scaffolds | 8,918,381 | 3.31 Gb | 2,627 bp | 195,104 | 980 bp | 496,991 | 706.92 | 275 | 286 |
| Redundans k81 | 1,157,969 | 2.10 Gb | 3,958 bp | 149,577 | 2,126 bp | 330,514 | 3,961.18 | 390 | 319 |
| Chromosomer k81 | 77,683 | 1.78 Gb | 263,097 bp | 5,018 | 56,379 bp | 3,077 | 19,504.19 | 505 | 88 |
| O. bimaculoides | 151,674 | 2.34 Gb | 485,615 bp | 1,300 | 215,581 bp | 3,077 | 15,346.35 | 773 | 28 |

Table 3. Assembly statistics for Octopus vulgaris. Statistics were generated with QUAST and a default threshold of 500bp. See text for details.
Technical Validation

Quality control. The quantity and integrity of the genomic DNA was analysed via agarose gel electrophoresis and with a NanoDrop spectrophotometer (Thermo Fisher Scientific; concentration of 1 μg/μl, A$_{260}$/A$_{280}$ = 1.84 and A$_{230}$/A$_{260}$ = 2.2). DNA integrity was analysed with Agilent Bioanalyzer 2100.

Quality control DNA library. To assess the quality of Illumina reads FastQC (www.bioinformatics.babraham.ac.uk/projects/fastqc) was performed on all raw data. Trimomatic v0.36$^{80}$ was not able to identify any significant adaptor sequence contamination within the raw data. The data were mapped to the PhiX control library (Illumina, Inc) using Bowtie2 v2.3.4$^{81}$ and no matches were found.

Sequencing depth assessment. We used jellyfish 2.2. 10$^{82}$ on the raw read data using kmer size of 17 bp. This resulted in a depth of sequencing histogram (Fig. 1) showing sequencing depth peak of around 76x. Using the kmer depth curve and the cumulative read depth (Fig. 1), repetitiveness, and heterozygosity was conducted independent of the genome assemblies (see Tables 2 and 3). The genome was estimated to be around 2.4 Gb in length with a relatively high heterozygosity rate (>1.1%) and large repetitiveness (>50%).

Genome properties and future steps
To gain information on the genetic distance between the two closely related species *O. vulgaris* and *O. bimaculoides*, we mapped all the available raw sequence data from *O. vulgaris* against the genome of *O. bimaculoides$^{83}$ and found that 74–84% of the data aligned, but that a high percentage (20–50%) was able to align multiple times. The significant proportion of multiple mapping reads suggests that, similar to the *O. bimaculoides* genome, *O. vulgaris* genome has a large number (at least 50%) of repetitive elements, confirmed by the cumulative read depth analysis
Ab initio repeat analysis using dnaPipeTE\cite{4} revealed similar classes of octopus specific short interspersed nuclear elements (SINE) to be over-represented (Fig. 2), yet the proportions were strikingly different, despite the close phylogenetic distance. This indicates high activity of repetitive elements in the common octopus genome.

Profiling *O. bimaculoides* regions with read coverage from *O. vulgaris*, we found that 23,509 *O. bimaculoides* genes were covered at 90% or more of their coding sequence length by *O. vulgaris* reads (Fig. 3). Approximately 50% of those genes had a Pfam annotation, including gene families previously reported to have undergone major expansions in the *O. bimaculoides* genome, such as zinc fingers and protocadherins. This is in strong contrast to only 1,570 *O. bimaculoides* genes with no *O. vulgaris* read coverage, with just 14% of those having a Pfam annotation. Those candidates represent very recent novel or highly diverged genes and their number indicates...
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**Author Contributions**

I.Z. and G.P. provided material for DNA sequencing and drafted an early first version of the manuscript. S.T. and M.Y. generated the data and performed a preliminary analysis. K.H. and G.E.M. further analysed the data and run following steps, and developed a further version of the manuscript. O.S. contributed to the conception of the work and contributed to data analysis and to paper writing. M.Z. established the database resource. G.F. and G.P. conceived the work, performed the sampling and contributed to the paper writing. All authors contributed to writing and editing the final manuscript.

**Additional Information**

**Competing Interests:** The authors declare no competing interests.

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