Methods

Identification of Journal Articles

To investigate the use of biological inspiration in the urban self-organisation literature we identified five urban design related journals (Built Environment, Environment and Planning B: Planning and Design, Journal of Urban Design, Urban Design and Planning, Urban Design International) and five biology journals (Biology Letters, BMC Cell, Ecological Modelling, Ecology Letters, Theory in Biosciences), and extracted all articles mentioning self-organisation between 2000-2016 (Urban Design and Planning started in 2008 so its literature search spanned 2008-2016).

Articles were searched for using the advanced search tools in Google Scholar and Web of Knowledge. To account for differences in the spelling of self-organisation we searched for "self-organisation", "self-organization" for each of the 5 journals, limiting the results to since 2000. In Web of Knowledge we used "self-org*", the asterisk allows any combination of letters to follow the initial string. Once duplicates were removed 92 urban planning articles and 388 biological articles were downloaded.

For an article to be included in the study it had to mention self-organisation at least once in the body of the text, be a research or review article, thus eliminating articles such as editors' summaries of special issues and book reviews, and have been published between 2000 and 2016, articles published online in 2016 were included. In total 69 urban planning articles and 205 biological articles were found to meet the criteria and were examined further.

Data Collection

25 biological terms were selected because they either embodied fundamental or emerging concepts in biology e.g. evolution and epigenetics, were known to have been used previously by urban researchers e.g. metabolism, were relevant to self-organisation e.g. collective behaviour, or particularly relevant to the study of humans e.g. cultural evolution (a complete list is given in Figure 1). The frequency of each of these terms was recorded for each biological and urban paper. For a term to be counted it had to appear in the abstract or body of the article. Terms appearing in the title and sub-headings, figure captions, reference section, appendices etc were not counted.

All urban papers were read to identify how biological terms were used. The basic list of 25 terms was extended as the papers were read to ensure that biological comparisons that did not use one of our 25 terms were captured. Biological terms were classified by the mode of use: analogy, metaphor, simile, other. We employed definitions from the Oxford Dictionary of English (2017) to interpret these terms. As such, simile is defined as:

'*a figure of speech involving the comparison of one thing with another thing of a different kind, used to make a description more emphatic or vivid*',

metaphor as:

'*a figure of speech in which a word or phrase is applied to an object or action to which it is not literally applicable*',

and analogy as:

‘*a comparison between one thing and another, typically for the purpose of explanation or clarification’*.

However, there is much overlap between the use of these terms. Indeed, a simile is actually a type of metaphor, and analogies are often comprised of similes and metaphors, and so, we further distinguished simile as containing the words ‘*like*’ or ‘*as*’, and analogy as being a logical argument of similarity. As such, in our analysis, ‘*city is an organism*’ would always be noted as an analogy because (i) by itself it doesn’t make the description of the city more vivid or emphatic, rather it requires further metaphors or similes to clarify it, (ii) the phrase has a strong history of inspiring analogical thought, and as such, even alone, the reader may infer comparison of similarity. ‘*Arterial road*’, however, would not automatically be considered an analogy because no deeper meaning than main transport route is implied. ‘Arterial’ is a more vivid and emphatic synonym for main route than the word main.

For each urban paper the topic of the paper, whether or not an analogy was present and if it related to self-organisation was recorded. If a biological analogy was present the urban and biological agents that the analogy predominantly related were recorded (e.g. city - organism). Biological analogies were assessed on their clarity, biological soundness, depth and application using a scale of 1-5 (1=low, 5=high). Clarity referred to the unambiguousness of the analogy being made. Biological soundness to the accuracy of the biological information. Depth measured the amount of biological information included in the analogy, whilst application assessed the fit of the biological analogy to the urban realm.

Statistical Analyses

All statistical analyses and data visualisations were produced in RStudio using R version 3.4.0. In total, there were seven biological terms (including self-organisation) that appeared in one third or more of the urban planning papers (23 or more papers). The seven terms were 'adaptation', 'ecology', 'evolution', 'feedback', 'morphology', 'multi-level', and 'self-organisation'. The distribution of each term's usage was mapped using boxplots. As the data were non-parametric, two-tailed Wilcoxon-Mann-Whitney tests were used to examine differences in the likelihood that a particular term was used, between the two disciplines.

Mapping analyses were employed to compare differences and similarities in the handling of the 25 biological terms between the disciplines. Because the terms: 'cultural evolution', 'epigenetics', 'heredity', 'phenotype', and 'phylogeny' did not appear in the urban literature they were omitted from the mapping analysis. The Fructerman-Reingold layout was employed to distribute terms across the page, sending the least connected nodes furthest, whilst darkness of the lines between nodes was used to indicate the frequency with which the terms are used in the same paper.

The R library 'riverplot' was used to produce Sankey diagrams that graphically represent the frequency with which particular biological comparisons were employed in the urban literature.

To visualise the relationship between the clarity, depth, biological soundness and application of analogies, 3D scatterplots were employed as per Ligges et al. (2003). The points are anchored to a grid on the xy-axis to make clear their location. A linear model was calculated and plotted, resulting in a regression plane, from which the +ve (red lines) and -ve (blue

dotted lines) residuals are drawn. The fourth dimension is shown using different symbol types.

Results

The number of urban articles mentioning self-organisation remained relatively constant between 2000-2011, rising between 2011-2016, a trend consistent with the findings of (de Bruijn and Gerrits, 2018; SM2). The number of biological papers mentioning self-organisation decreased after 2011, resulting in more urban papers being identified that contained self-organisation in 2016 than biological papers (SM2).

Self-organisation was referenced across a wide range of urban design topics (SM3). Discussion of self-organisation took many forms from models elucidating the mechanisms of urban self-organisation (Daffertshofer, 2001), the use of techniques to look for indicators of self-organisation (Chen and Zhou, 2006; Porta et al., 2006), unplanned, local initiatives such as guerilla gardening groups (Ache and Ferowitz, 2012; Silva, 2016), techniques for incorporating self-organisation into the planning process (Rauws and de Roo, 2016), to a cursory mention of self-organisation at some point in the article, for example as a potential area of interest for future research (Janssen-Jansen, 2013), or an intrinsic aspect of urban complex systems (Vancheri et al., 2008).

Kant and self-organisation's biological foundations were rarely mentioned; instead discussion of the history of self-organisation focused on the 20th century (Partanen, 2015) when major developments in the modern study of self-organisation occurred in the physical sciences.

Biological Terms

All urban papers contained at least one of our biological terms other than self-organisation. Self-organisation was the only term to appear in all 69 articles; however it was not the most used, appearing 474 times compared to the most popular biological term, evolution, found 497 times in 55 of the articles.

The frequency of use of 'self-organisation' was found to be consistent between the biological and urban literature (W=6355.5, p=0.1944). The same was true for adaptation (W=6656, p=0.4371) and feedback (W=7072.5, p=1). 'Ecology' was found to be employed significantly less in the urban literature (W=10852, p<0.001), whilst, 'evolution', 'morphology' and 'multi-level' were significantly more common in the urban than biological literature (W=5733, p<0.05; W=5595, p<0.001; W=5318.5, p<0.001, respectively, SM4).

Mapping of the terms revealed further inconsistencies in connections between the two disciplines (Fig.1). Whilst all 25 of our biological terms appeared in the biological literature, 'cultural evolution', 'epigenetics', 'heredity', 'phenotype', and 'phylogeny' did not appear in the urban literature. Of these, in the biological word map, 'heredity', 'phenotype', and 'phylogeny' are found on the outside edge of the central cluster, whilst 'cultural evolution' and 'epigenetics' were more distantly connected (Fig.1).

In both disciplines the strongest link is between 'self-organisation' and 'evolution', and both are linked to 'adaptation' (Fig.1). In the urban papers 'self-organisation' is also tightly bound to 'ecology', to which it is slightly less closely connected in the biological literature. From here, the two disciplines differ notably. Whilst, the biological mapping stresses the

importance of ‘gene’, ‘mutation’, ‘natural selection’, ‘organism’, and ‘morphology’, the urban mapping highlights ‘morphology’, ‘feedback’, ‘multilevel’, and ‘organism’ (Fig.1).

This disparity and the discrepancy in central mapping of terms emphasises a key difference between the biological and urban realms. In biology, evolution is often defined in terms of changing allele frequencies in a population over time. New alleles enter a population in several ways e.g. mutation and immigration, whilst change is driven by gene flow, genetic drift and natural selection. Natural selection is the only mechanism that actively promotes organisms better adapted to their environment. Natural selection requires variation in the phenotypic expression of traits, that the expression of these traits is heritable between generations, and that these traits result in improved reproductive success. If so, individuals with beneficial traits reproduce more than individuals without beneficial traits, passing on those traits to their offspring, increasing trait occurrence in the population and so, the allele frequencies that underpin it. As such, the terms at the centre of the biological mapping all relate to biology’s central theorem, that adaptive traits are the product of evolution through natural selection.

Direct analogues of biological evolution have been largely absent in urban planning (Mehmood, 2010). Those that do so face a multitude of challenges including: defining urban genes, characterising urban genes to phenotype translation, identifying the units of survival and reproduction, and defining urban fitness.

Biological Comparisons

In depth review of the urban articles resulted in the identification of 66 biological terms, which were used 2371 times. Biological comparisons were found in 31.88% of the urban

articles. 15.94% of urban papers analogised the urban realm to the biological realm, 23.18% used metaphor, 7.25% similes (SM3). The total is more than 31.88% because some papers contained more than one type of biological comparison.

However, biological terms were more commonly used in a way *not* consciously invoking a biological comparison, e.g. “Cities are physical objects that display extreme variety of size and morphology” (Benguigui et al., 2001). Indeed, of the 2371 biological terms identified only 5.44%, 6.28%, and 2.91% were used as analogy, metaphor, or simile, respectively.

Of the 13 analogies identified, in 11 papers, 69.23% were made between entities at different hierarchical levels e.g. city–organism is cross-level analogy whilst person–organism is a direct level analogy (Fig.2). 38.46% of the analogies related directly to self-organisation. Where analogies were identified they were often found to be either unclear (mean=2, s.d.=1), and/or, of limited depth (mean=2.15, s.d.=1.07).; whilst, depth of analogy showed no connection with urban applicability of the analogy to the urban situation we found a positive association between the depth, and to a lesser extent the clarity, of an analogy and its biological soundness (SM5). The applicability of the biological analogue to the urban realm was found to be higher when it was both clearly conveyed and the biological content was accurate (SM5).

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