空间句法的发展：过去、现在、未来

Developments in Space Syntax: Past, Present and Future

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摘　要

本文就20世纪70年代后期开始到未来空间句法发展方向潜在的发展轨迹提出了见解。该领域过去的发展成果通过空间句法领域的主要出版物、会议论文集以及研讨会的贡献进行总结。在对科学产出的关键趋势进行回顾后，本文最后为该领域的未来发展提出了一系列的建议。

Abstract

This paper provides insights into development directions in space syntax, from its inception in the late 1970s to potential future trajectories. Past developments are synthesized from key publications, conference proceedings, as well as seminar contributions in the field of space syntax. A review of critical trends in science production is used to conclude with a series of recommendations to progress the field in the future.

关键词：空间句法；城市研究；方法论发展；开放科学

Keywords：Space syntax; Urban research; Methodological developments; Open science

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1 研究背景

在过去的 50 年里，空间句法领域已经发展出一套全面的理论和方法论框架，用于研究空间与社会之间的相互作用。20 世纪 70 年代初期，伦敦大学学院巴特莱特学院的比尔·希利尔（Bill Hillier）（1937—2019）和他的同事提出了空间句法的概念。此后，空间句法发展为一个庞大而多样化的国际研究领域。自 1997 年以来，来自世界各地的研究人员在两年一度的国际空间句法研讨会上相会，带来越来越多相关领域的研究成果。今天，这种研究方法已在世界各地的实践中得到广泛应用，涉及的项目小至对建筑的小规模干预，大到全国范围的战略总体规划。空间句法研究所提供的证据拓宽了我们对城市基本功能及其空间的理解。

自空间句法理论提出以来，该领域经历了一系列重要的发展阶段，其特点是引入了核心理论和方法概念以及用于测试这些概念的科学方法和工具。然而，其中最值得注意的是空间组构的概念。它将空间定义为一个具有相互关系的事物。这种概念分析重塑了框定研究问题的方式，即采取了空间优先的视角。它允许对复杂的空间组织，例如建筑平面、社区或城市，进行系统定量的描述和比较，随后将这些空间类型与人类活动联系起来。其理论基础是任何人类行为都发生在物理空间中。这样，这些行为将会留下痕迹，并最终塑造出物理空间本身，进而反过来影响未来人类的行为[1]。利用空间布局，希列尔和他的同事们能够证明，空间不是社会的副产品，也不是人类行动的单一背景，而是随着时间的推移，社会建构及再生产的积

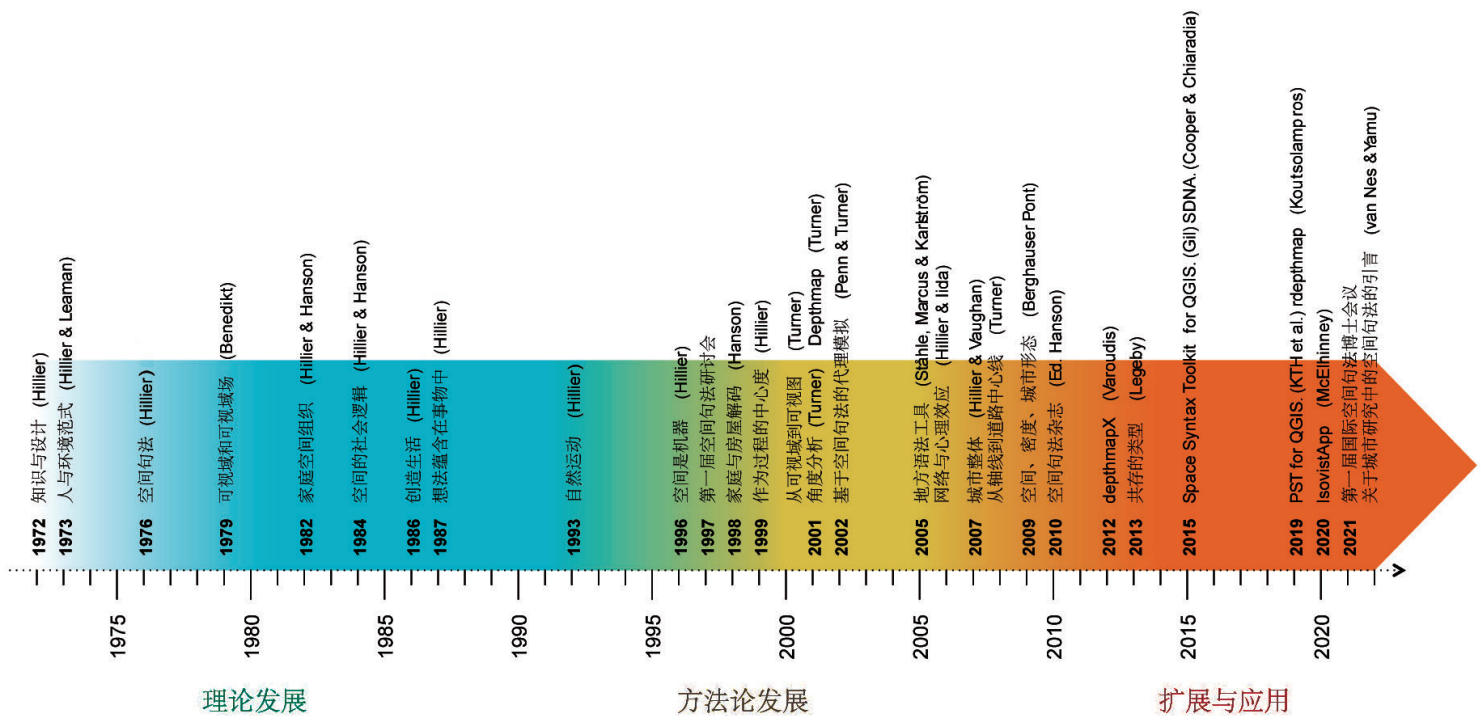

图1 / Figure 1
空间句法领域的关键发展阶段/ Key developmental stages of the field of space syntax

极驱动力 [2]。

空间句法为建筑和城市设计学科带来了全新的定量科学思维方式。它还恢复了地理学领域的一系列研究，即在 20 世纪 60 年代不再受到重视的“区位分析”。这其中有部分原因是对环境决定论的担忧。空间句法把关注点从决定论转移至人的潜力，进而解决了该困境。自其被引入以来，空间组构的概念已经引申出大量的新概念及对现有概念的改进。理论和方法框架以不同的方式发展着。其发展速度如此之快，以至于在比较以往对相同现象进行研究的文献所揭示的证据时，需要特别小心。

此外，在过去 10 年的建筑、城市设计、规划和地理领域中，定量和参数化方法得到了越来越多的应用。人们日益认识到建成环境是造成社会、经济和环境不平等的一个因素。这凸显了对城市物理空间的量化、评估和比较需要更好的衡量方式和可复现的客观方法。虽然空间句法多年来一直处于这些发展的前沿，但相关学科正越来越多地融合和推进这种思想。开放数据变得越来越易于获得，空间数据科学方法的出现，加速了这一趋势。这带来了许多不同的定量方法，以便填补方法论在这方面的空缺。这种替代性开源空间分析工具的日益普及，对可复现性和可复制性以及对跨科学因果推理的日益关注，为空间句法领域带来了令人兴奋的机会，但同时也需要对方法论进行（再）发展。

鉴于这些进展，现在似乎是反思空间句法领域过去和现在发展轨迹的合适时机，以便深入了解未来可能发生的发展轨迹和发展潜力。因此，本文有两个目的：①对空间句法领域的发展进行概述；②对该领域的机遇和潜力进行展望。具体来说，我将从空间句法重要出版物的回顾和分类开始，确定各发展阶段。接下来笔者将通过对国际空间句法研讨会上发表的会议论文的文本定量分析结果，对该领域的理论产出发表见解。此外，对空间句法实验室研讨会以及第一届国际空间句法博士在线会议前沿研究的回顾，将用于对空间句法当下的发展进行概述。最后，我将把这些见解与整个科学的重要发展成果结合起来，以便对整个空间句法领域提出发展方面的建议。

2 过去的发展

自 20 世纪 70 年代初出现以来，空间句法的理论和方法不断地被发明、拓展和完善。此外，该方法介入了大量不同空间尺度的子领域。这种复杂性说明了在特定时候定义一个完整领域的困难性。然而，通过关键概念以及出版物被引用的频率识别出重要的空间句法出版物并观察它们后发现，分析工具和关键事件的发布可揭示出重要的发展阶段。空间句法领域的发展可被分为 3 个关键阶段，即① 理论发展；② 方法论进步；③ 扩展和应用（图 1）。这些核心阶段之间并没有很明确的划分界线，而是相互模糊交织在一起。此外值得注意的是，尽管程度不同，所有阶段都呈现出相似的特征。此外，

被选择的出版物并不一定能完整代表该领域，而应被视为提炼和代表世界各地众多研究人员科学成果的尝试。随后的部分将概述每个发展阶段的特征。

2.1 理论发展

该领域的第一个发展阶段可以被描述为从1970 年持续到 1999 年的理论发展阶段。希利尔和他在巴特莱特学院的同事在此期间阐明了空间句法的大部分基本理论和概念。这包括全领域被引用 [1] 最多的 3 份出版文献，即《空间的社会逻辑》[3]（被引用 9,625 次）《自然运动》[4]（被引用 2,283 次）和《空间是机器》[5]（被引用 6,292 次）。此外，这一时期还发表了诸如《空间句法》[6]《家庭空间组织》[7]《创造生活》[8]《想法蕴含在事物中》[9]《寻路途中寻找建筑》[10]《家庭与房屋解码》[11] 等重要文献以及对这些文献产生影响的文献，例如迈克尔·贝内迪克特（Michael Benedikt）的《可视域和可视场》[12]。通过阅读与城市设计领域相关的 3 篇被精选文献，我认为理论发展阶段对该领域而言至关重要。这是因为它意味着 3 件事：① 它为建成环境的科学研究和空间与社会之间的关系提供了方法论基础；② 它为社会在空间中自我形成的方式提供了理论概念及其解释；③ 它确立了对我们理解城市空间功能而言至关重要的理论机制。这一时期大约在 1997 年左右结束。当时召开了第一届国际空间句法研讨会，它为该领域后续的进展提供了重要推动力。

希利尔等人里程碑式的同名出版文献中首次提到了“空间句法”[6]。这篇论文受到希利尔和他的同事阿德里安·利曼（Adrian Leaman）、约翰·马斯格罗夫（John Musgrove）和其他人 20 世纪 70 年代初期《知识与设计》[13]《人与环境的范式》[14] 等一系列出版物的影响。这些文献成为重要的入门读物，因为它们为建成环境的科学研究开辟了道路。在《空间句法》中，希利尔和他的同事关注“不同社会如何以及为什么通过建筑形式和聚落模式产生了不同的空间秩序”这些问题 [6]。为此，他们提出通过数学方式描述和分析空间组织中的关系。然后，他们将这些数学表达与关于居民使用空间方式的信息联系起来，以便深入了解塑造它们的社会。这里的重要命题是空间句法的，是一组构成空间模式的组合规则，它们反过来又可以承载意义。通过理解空间的句法，希利尔等人建议，我们也许可以讨论居住在其中的人们。《空间句法》概述了以空间为先的对空间与社会相互关系研究的基本原理。希利尔后来解释说，《空间句法》“是第一篇认为可以以科学的方式研究建筑空间的文献 [15]”。

8 年后的 1984 年，希利尔和汉斯（Hanson）出版了他们的开创性著作《空间的社会逻辑》。这本书介绍了一种全新的空间社会理论，得到了历史人类学、考古学和人种志学数据的支持。希利尔和汉斯将《空间句法》中表达的最初想法发扬光大，并将其发展为一套系统的方法。具体来说，他们提出通过图形表达来描述空间的模式。他们进一步阐述了这些方法如何为社会规则和等级制度嵌入空间的方式提供重要见解。在此期间，他们使用了一系列从小型个体空间到村庄聚落等不同尺度的示范性空间组织方式进行解释。这样，他们抓住了城市空间的基本功能，即涌现。希利尔和汉斯认为，城市空间是由个体随着时间的推移逐步创造和塑造出形态的，并没有全局结构的总体概念，但小规模的变化就可能对全局产生显著影响。这样关键的特性便允许对局部的空间进行独立研究。此外，《空间的社会逻辑》引入了一系列植根于社会理论的概念（例如，描述性检索、空间—跨空间、基因型—表现型 [3]）以及能够研究空间与社会相互关系的方法论概念（例如轴线、凸空间、整合、全局—局部 [3]）。

1996 年，希利尔发表了代表作《空间是机器》。在这部作品中，他以《空间的社会逻辑》为基础，强调了空间组构的概念以及自第一版以来的理论和方法论的发展。值得注意的是，这些先前的出版物包括诸如《创造生活》[8] 增加了选择度 2[16] 和可理解度的概念；《自发活动》[4] 引入了同名的概念，描述了由空间布局本身决定的行人活动所占的比例。这是一个塑造潜在城市空间的关键机制。在众多例子中，希利尔展示了空间组构如何成为建成环境支配日常生活的关键机制 [5]。希利尔使用共同存在 [5] 和共同意识 [5] 等概念，进一步阐述了空间布局对社会凝聚力所带来的潜在影响。就像在《空间的社会逻辑》叙述的那样，《空间是机器》不仅提供了分析工具，而且扩展了社会空间概念的框架，以解释和描述其分析结果。通过为其描述提供分析方法和概念，希利尔有效地克服了空间的非话语性问题 [5]。利用 20 世纪 90 年代初算力不断增长的机会，《空间是机器》还提出了新的方法，将图论指标应用于更大的空间组织，乃至整个城市；并在一系列富有洞见的地图可视化中对其进行展示——迄今为止，这些方法使空间句法分析和它们的彩虹色图例无法分离。

2.2 方法论发展

该领域的第二个发展阶段发生在 1999 年至 2010 年，包括关键的方法论发展。空间句法的主要特点一直是理论构建与方法论 / 分析发展之间的密切联系。然而，这一时期的方法论发展尤其具有代表性。参数化方法和将空间句法应用于复杂城市范围系统的工具创建均取得较大发展，由早年对理论发展的关注转向加强新算法的开发，来探索建成环境与人类活动行为之间的关系。虽然理论产出仍在继续，但随着诸如《作为过程的中心度》[17]《网络与心理效应》[18] 和《城市整体》[1] 等重要出版文献的出现，这一时期尤其以方法论成果为特征，例如《从可视域到可视图》[19]《角度分析》3[20-21]《基于空间句法的代理模拟》[22]《从轴线到道路中心线》[23] 或《空间、密度和城市形态》[24]。

正是在这个时候，与阿拉斯代尔·特纳（Alasdair Turner）（1969—2011）以及尼克·道尔顿（Nick Dalton）等计算机科学家的合作，带来了用于分析建成环境和模拟人类行为的定制软件和算法解决方案。这些基于实验和模拟的计算方法被用作进行“思考”[2] 的工具，加深了我们对人类行为的理解 [25]。这其中包括 OmniVista[26]——一种用于可视域场和路径分析的工具；Depthmap 的第一个版本 [27]——一种用于可视图分析（visibility graph analysis, VGA）的工具 [19]。Depthmap 的开发持续了多年，并囊括了额外的功能，例如凸空间和轴线分析、角度线段分析 [21] 和基于代理的模拟 [22]。角度线段分析的引入不仅改进了对人类出行流的建模方式，而且还为人类路线选择的决策机制提

供了更深入的理解[18]。直到今天，Depthmap仍然是世界各地许多研究人员进行空间句法分析的基础。不久之后，施塔赫勒（Ståhle）、马库斯（Marcus）和卡尔斯特伦（Karlström）[28]提出了场所语法工具，它将引力模型的原理与基于空间句法的空间布局方法相结合。施塔赫勒等人的工具已完全集成到地理信息系统(GIS)中，这开辟了流水线化的工作流程，更容易整合越来越容易获得的位置信息。

也是在此期间，基于矢量地理信息的大规模数据集变得可用。空间句法领域是在城市分析中较早采用此类数据的领域——不仅在技术层面（如场所句法工具或Depthmap），而且也受到理论研究的驱动。这是与城市建模其他替代方法（例如，在城市分析的新领域）的关键区别。这类替代方法至今仍然存在，例如，特纳[23]提出并测试了与道路中心线数据的结合。现在这种数据类型已经成为每个现代导航应用的基础。道路中心线数据的应用在社区中得到了充分的支持，因为它以自发生产的地理信息或政府数据源的形式被大规模提供。

方法论发展阶段在《空间句法杂志》(*Journal of Space Syntax*, JOSS）第一期出版前后的几年内结束[29]。JOSS为空间句法理论和方法论发展的公开提供了专门的落脚点，也是该领域的一个重要里程碑。

2.3 扩展与应用

现在仍在持续的第三个发展阶段始于2010年。该阶段最适合用方法论的不断扩展和应用来描述。之前的发展阶段提供了全新的基础理论和方法论，而扩展和应用阶段的特点是主题多样化，空间句法在多个领域和案例研究中得到广泛使用，方法和工具日益方便，可获取性好。该领域的增长幅度可以通过查看所有主要以英语出版的书籍中“空间句法”双连词的使用来估计（图2）。2010年之后，我们可以观察到“空间句法”的急剧增长，其与“城市形态”以相似的轨迹发展。在过去的10年中，世界范围内与空间句法相关的成果和应用都出现了显著增长。这部分是缘于该方法在全球范围内的成功应用，也缘于人们努力使相关工具和算法变得可被公开访问。这一发展的重要标志是一系列开源的空间句法应用程序的发布。例如，塔索斯·瓦鲁迪斯（Tasos Varoudis）在2012年发布的depthmapX（可用于Linux、OSX和Windows的移植版本）、用于QGIS的Space Syntax Toolkit[30]、R语言的rdepthmap包[31]以及QGIS的“地方语法工具”[32]。

这种开源软件为整个研究界带来一系列好处，包括对软件及其代码的免费和开放访问、更快地识别和修复错误、与用户群的接近和直接反馈闭环、成为社区活跃开发者的众多机会（即自由检查、修改、和重新分发软件）、算法功能及其实现的透明度和开放性、随附手册的可获得性。这里每一项好处都在depthmapX等开源软件的广泛应用中发挥了作用。方法、工具和数据的日益普及也使得空间句法方法在越来越大的尺度中得到应用，从城市级[33]到子区域[34]到区域[35]，最终到全国范围[36]。这也突出了现有空间句法算法在计算网络中心性方面的算力瓶颈。

然而，社区的发展和日益方便获取的工具并非没有给该领域带来挑战。在模型构建[37-38]、指标计算、和算法执行方面，不同应用领域之间存在越来越多的不一致。沙明（Sharmin）和卡姆鲁扎曼（Kamruzzaman)在现有一份对空间句法指标与行人活动之间关系的研究案例中强调了这一问题[39]。在创建基于道路中心线空间句法模型的过程中，许多作者在克服开发通用方法困难的时候，以上问题也很明显[40-43]。

同时，在此期间，理论和方法论的发展步伐未曾停滞。例如，标准化最小角度选择度的引入[44]、sDNA的发布[45]、DeCodingSpaces工具箱[46]以及最近的IsovistApp[47]等几个例子。此外，该领域的几位前博士生和研究人员出版的书籍中采用了空间句法方法的原则和概念，将其扩展和应用到不同的主题上。例如，基于城市和建筑的研究议题[48-49]、空间在社会中的作用[50-53]、文学、叙事和想象[54-56]以及特定的研究领域——例如，健康护理设计[57]。此外，对于该领域的发展至关重要的是，几位作者概述了空间句法教学的课程[58-59]。其中，最近范内斯（Van Nes)和亚穆(Yamu)[60]发表了较为全面的成果。

在许多方面，扩展和应用阶段可以看作是整合的过程。正如卡里米(Karimi)[61]所指出的，如今“空间句法研究不再被视为一个专业或全新的领域”，相反，空间句法理论和方法的广泛应用表明该方法在相关学科中也得到普遍接受。然而，大多数跨学科研究是从空间句法领域内部驱动的，而不是从相关学科开始的（这可能部分源于过多的概念，或现有研究中潜在的不一致之处）。从应用空间句法研究的各领域来看，这一过程所涉及的范围变得显而易见（图3）。

2.4 空间句法研讨会和概念发展轨迹

然而，最能证实该领域发展和应用的，是两年一度的国际空间句法研讨会。自1997年以来，该会议已在英国、巴西、美国、荷兰、土耳其、瑞典、智利、韩国、葡萄牙、中国、挪威举办了13次国际研讨会。在这段时间里，研究界已经发布了1,500多份经过同行评审的会议论文集(图4，左)，其中包含超过600万字书面文字。这包括来自50多个国家的1,100多名作者和合著者的作品。会议和专题讨论会是了解研究领域科学成果的重要场所。它们是研究人员亲自会面以展示、讨论和测试新想法和发现的论坛。它们通常被记录在会议纪要中。这些会议纪要汇总起来，可以提供一个了解该领域过去、现在和未来发展的窗口。因其定期出版的频率，空间句法会议论文集对该领域的发展随时间的推移持续提供各种见解。通过定量地研究文本中特定术语的使用方式，对科学成果的见解便可得到推断。

2019年，克伦茨（Krenz）等人在第12届国际空间句法研讨会（International Space Syntax Symposium, ISSS）上展示了这种定量文本分析的结果。他们使用了从ISSS成立到2017年期间在ISSS上展示的所有会议论文集的正文，分析了随着时间的推移，各类概念出现的频率。这样，他们创建了一个相互连接的概念网络，估计了它们的使用轨迹。他们的分析表明，相互关联的概念在网络中构成了集群，并且这些集群具有不同的轨迹[62]。最值得注意的是，植根于社会理论的概念（例如，社会团结性或描述性检索）在该领域中的使用频率正在下降。同时，方法论概念的使用频率呈上升趋势，特别是基于网络的中心度、线段角度分析和与之相关的概念。例外的是与轴线分析相

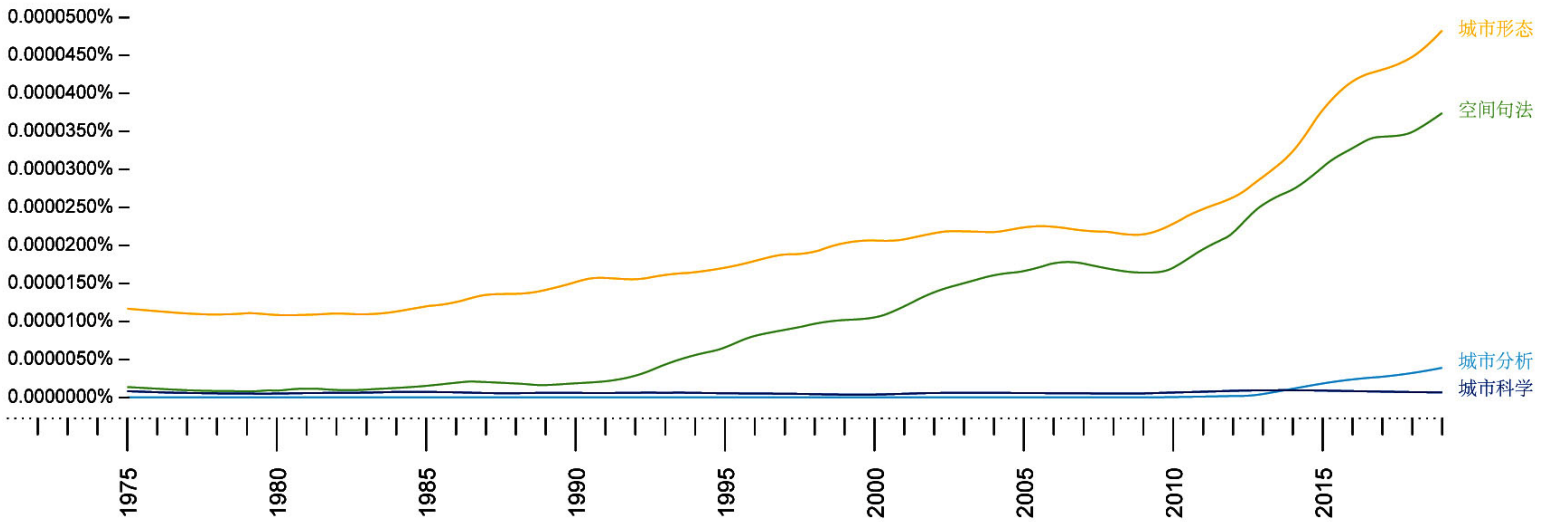

图2 / Figure 2
“空间句法”“城市形态”“城市分析”和“城市科学”的Google Ngram/Google Ngrams for the terms “space syntax”, “urban morphology”, “urban analytics”, and “city science”

关的概念（例如，全局到局部，或可理解度），其使用频率正在下降。基于建筑的可视图分析和可视域分析形成的集群，呈现出不同类型的轨迹，这表明基于建筑尺度研究的持续发展。此外，每个会议年度新出现的概念数量多年来持续下降，这显示出概念全新性的下降（图 4，右），也表明该领域走向整体融合，其中提出的概念以已建立和经过测试的方法得到接受。作者们总结认为，该领域出现了“技术转向”[62]，他们描述了从理论产出向技术进步的转变过程。这一观察证实了已得到确定的发展阶段。这样，越来越多地结合参数化方法的过程，在所有科学领域都可以被观察到。

总之，空间句法领域随着时间的推移展现出持续发展的态势。该领域过去的发展可以被分为 3 个更广泛的发展阶段。它们的特点分别是早期的理论产出、方法的大规模提出以及在世界范围内越来越多地使用这些方法的扩展阶段。理论产出、追求概念新颖性、植根于社会理论的概念使用则明显下降，同时伴随着方法论应用的增加。

3 现时的发展

除了过去的发展，通过对该领域正在进行的活动以及早期职业研究的观察可以了解到当前发展及其对未来研究的影响。为此，我将观察第一届国际空间句法博士在线会议的成果产出以及在空间句法实验室研讨会上展现的前沿研究。这将有助于了解空间句法领域当前科学研究产出所聚焦的主题。

该领域的发展为引入第一届国际空间句法博士在线会议带来了机会。博士会议的提议源于 COVID-19 大流行导致的国际空间句法研讨会的推迟以及为该领域博士生正在进行的研究提供一个论坛的初衷。会议由以阿克里斯·范·内斯（Akkelies van Nes）（西挪威应用科技大学）、玫塔·伯格豪瑟·庞德（Meta Berghauser Pont）（查尔姆斯理工大学）和劳拉·沃恩（Laura Vaughan）（伦敦大学学院）为代表的国际空间句法指导委员会临时执行委员会发起，吸引了 41 位博士投稿。他们的研究涉及空间句法理论和方法的应用[63]。这些成果的主题范围可一定程度上指代研究成果及其未来可能的产出。这 41 名博士生中的 18 人还在次年第 13 届国际空间句法研讨会上展示了他们的成果。这表明下一代学者正在成为空间句法领域的研究主力。

从广义上讲，这些研究生的研究工作可被分为七大主题，即交通、社会和政治空间、形态学、复杂建筑、遗产和考古学、绿地以及城市空间，每一主题都具有各自的成果和子分类，大多数成果属于城市空间组，包括聚焦于不同尺度城市空间的项目，特别是郊区和周边地区、微观经济活动（例如，城镇中心、零售和其他与土地使用相关的活动）以及对共存现象的研究。在这一组中值得注意的是杨宇峰的成果。他阐明了封闭式和非封闭式住宅区对中国武汉市的社区凝聚力的影响[63]。第二大组是复杂建筑，包括研究在建筑尺度上的各种现象（例如，寻路、建筑与街道的界面）和复杂建筑类型（例如，博物馆和展览空间、学校和教育环境、工作场所、医院和护理环境）。这一系列研究的典型例子是克里斯塔拉·普萨蒂（Chrystala Psathiti）的成果。他使用时空社会方法评估了塞浦路斯初级中学建筑的教育环境[63]。交通组涵盖交通规划领域的主题。该领域在空

图3 / Figure 3
现时与空间句法研究相关的学科与主题领域/ Present adjacent disciplines and thematic fields in space syntax research

间句法研究方面具有悠久的传统，其研究成果范围涵盖了对行人出行、自行车设施和出行方式划分的研究以及对联合交通网络进行建模的全新方法，特别是陈伯伦（Po Nien Chen）在多等级、多出行方式网络建模方面的成果为该领域做出了实在的贡献[63]。社会和政治空间组内的成果侧重于空间实体对社会和政治政策的影响，这些特点对热点话题做出了重要贡献，例如犯罪、种族多样性和种族隔离、性别差异以及公共住房。在这方面，迈克尔·利夫西（Michael Livesey）的工作值得一提。他研究了 20 世纪 70 年代中期英国政府的“犯罪化”政策如何在北爱尔兰的城市地区和监狱设计中得到体现[63]。遗产和考古学组的成果主要关注作为遗产研究的工具用于和考古研究、公共空间的历史、文化导向的行人活动相关的数据生成。这里值得注意的是保利娜·科纳热夫斯卡（Paulina Konarzewska）把获得的历史道路网应用于考古研究领域的工作[63]。形态学组的贡献包括关于城市几何特性的研究，特别是沿海城镇以及空间组织语言。这些研究中的典型例子是毛里西奥·佩雷拉·马丁斯（Mauricio Pereira Martins）的成果，他调查了沿海城镇边缘城郊区域的中心度[63]。最后，越来越多的研究人员将他们的工作重点放在绿色空间上，包括描述空间属性（例如，闭合度）的方法和发展绿色空间网络的方法。例如，瑞纳·马艮（Rina Magen）的成果调查了以色列特拉维夫都会区邻里公园和林荫大道的空间特性[63]。

空间句法实验室研讨会[4]将研究人员和学生们聚集在一起，分享他们在建筑、城市空间、社会交汇处的研究成果。该系列由巴特莱特学院国际知名的空间句法实验室组织，由国际特邀演讲者、伦敦大学学院研究人员、博士生组成，就我们如何理解、分析和设计建筑和城市等问题提供了不同的观点。在过去的一年中，在线研讨会接待了 11 位不同的国际演讲者，吸引了来自 80 个不同国家的 1,100 多名参与者。演讲者包括张灵珠和基亚拉迪亚（Chiaradia）[64]——他们展示了如何在角度分析中使用三维信息改进人流量的预测。弗雷德里克（Fredrick）和文纳鲁奇（Vennarucci）[65]提出了一种将三维虚拟现实方法与空间句法分析相结合的新型考古研究方法，以探索罗马房屋的作用。马丁·比利克（Martin Bielik）[66]提出了一种方法来分解空间布局和吸引点对行人出行分别的影响。康斯坦斯·德森芬特（Constance Desenfant）详细阐述了建成环境如何影响女性的方向感和安全感。保罗·桑蒂（Paolo Santi）[67]提出了一种基于向量的定向最短路径的路线决策替代方法。西蒙斯（Simons）[68]的成果是将城市形态学方法与机器学习方法联系起来，以检测和预测行人尺度上的城市原型。研讨会展示了当前的研究如何涵盖大量主题以及相关领域的定量研究如何越来越多地融合和扩展空间句法的基本思想。

总体而言，博士项目和前沿研究的例子表明，空间句法领域的主题多样性是十分显著的（图 3），他们强调了现有方法如何越来越多地被应用于相关学科。然而，只有少数研究正在解决紧迫的社会问题，例如气候危机、健康、社会及政治不平等、歧视与边缘化。与 21 世纪初期的方法论发展阶段相比，这些项目几乎没有方法论上的新颖性。此外，空间句法的基本思想在相关学科中的结合为方法论的发展带来

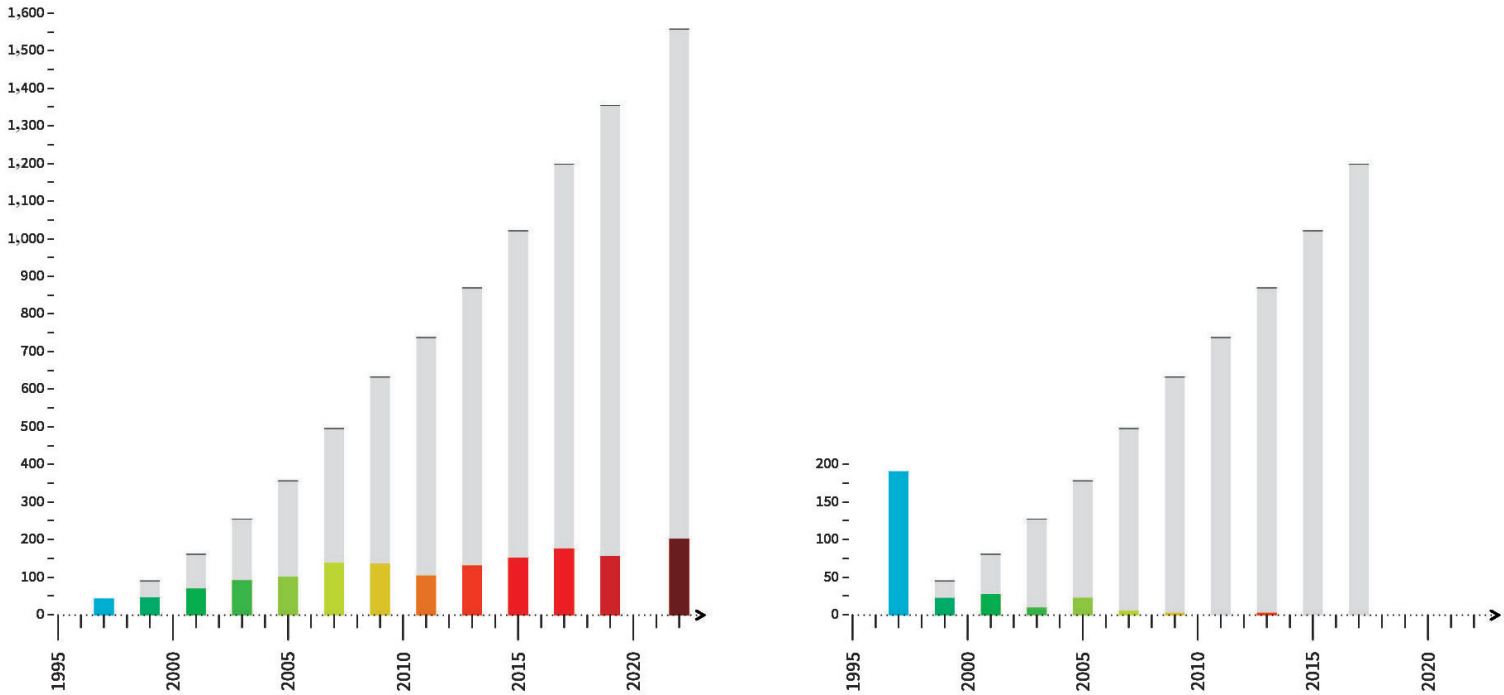

图4 / Figure 4
每年新增和累计的空间句法研讨会论文集总数量（左）与每年新引入的概念数量（右）/ The number and accumulative of total number space syntax symposium proceedings per year (left), and the number of newly introduced concepts per year (right)

了大量机会。空间句法方法以关于人类交互、感知、认知和经验的理论考虑为基础，这是该方法整体上看尤其特别的特点。然而，缺乏从空间句法领域推动新方法论发展的风险，可能会削弱这些空间句法理论基础的重要性。这方面的一个例子是波音公司[69]开发的 OSMnx 工具。该工具提供了一个框架，用于从自发地理信息（即 OpenStreetMap）中自动提取道路中心线数据，并使用基于图网络的中心度指标进行分析[5]。该工具广受欢迎（被引用 880 次）并应用于开创性研究[70]和具有全球政策相关性的研究[71]。OSMnx 能得到广泛应用的原因之一是其开源的基于代码的框架、在线文档，而且能通过 Python 编程语言轻松实现。为了能融入空间句法未来的发展中，这些特性将变得越来越重要。

4 空间句法科学生产与发展潜力的轨迹

在这节中，我将使用科学界普遍存在的 3 个关键趋势来概述与空间句法领域相关的重要方向，即① 数据科学方法的日益普及；② 开放科学方法的驱动力；③ 以确定因果关系为目的。

21 世纪的第一个十年，信息呈指数级增长。随着移动设备、相机、遥感、物联网的广泛普及和可负担性以及政府和企业管理任务的日益数字化，数据收集速度大大加快，于是就出现了“大数据”，即对于传统计算机软件来说太大或太复杂的数据集。这种结构化和非结构化数据集为获取知识和了解行为模式提供了充足的机会。到目前为止，工业化世界中虚拟的和物理空间中的任何人类活动都可能会留下数字痕迹，这使得记录人类在社会层面行为的信息日益丰富。同时，挖掘和分析此类数据集的工具和方法也呈爆炸式发展。这些工具、方法、流程和算法的结合形成了跨学科的数据科学领域及与其相关的人工智能和机器学习混合领域。将双连词“空间句法”“城市分析”“城市科学”和“城市形态”，与“数据科学”和“机器学习”的出现进行比较时，这种发展程度变得更为明显（图 5）。与“空间语法”术语相比，“数据科学”的使用频率高 10.96 倍，“机器学习”的使用频率高 22.38 倍。随着数据科学方法越来越多地融入各科学领域，这种发展趋势将很可能会继续下去。

此外，数据科学有一个新兴子领域是空间数据科学[6]。它在分析中结合了空间数据的独特属性。空间数据科学领域的基础是通过新的方法和工具将空间信息考虑进来。这个过程中，不是把空间信息作为通用变量，而是利用其属性，例如位置、距离、空间关系或交互等作为分析的基础。时空信息日益增长的可获得性刺激了这些新方法开发的需求。这些时空信息是由不断进行的测绘工作（例如，OpenStreetMap 或基于卫星的航空影像）、精确地理位置的收集（例如，通过手机的 GPS 跟踪、健身设备，或在社交媒体上的主动分享）以及现有信息的地理参考产生的。（空间）数据科学方法获得成功的一个因素，除了在处理围绕（空间）大数据问题的概述质量之

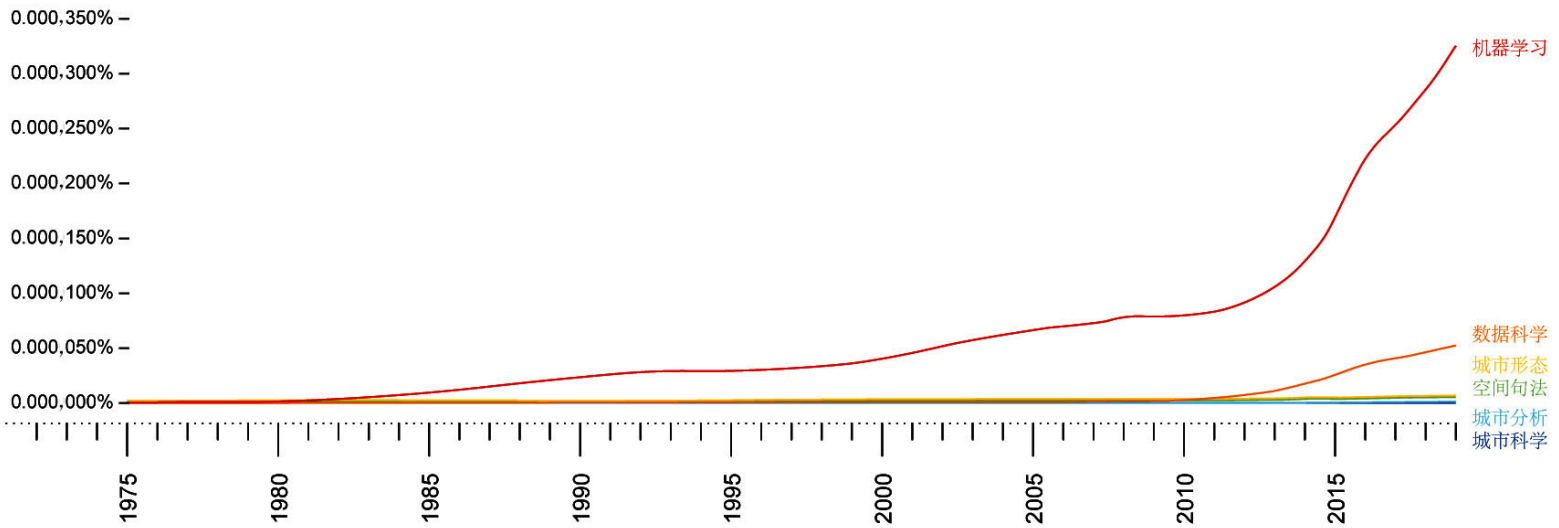

图5 / Figure 5
选定科学领域的双连词的Google Ngram/ Google Ngrams for bigrams of selected scientific fields

外，是它们的可访问性、可再现性和开放的科学方法。在 COVID-19 大流行的推动下，政府和学术界对开放科学方法的需求不断增加，这不仅需要开放可利用的工具和方法，还需要可复现的工作流程、数据集和计算环境。

实现这种开放科学方法的一种方式是使用开放编程语言（例如 R 或 Python）和计算性笔记。R 和 Python 在数据科学家中都特别受欢迎，因为它们是独立于平台的语言，与其他编程语言（例如 C、C++ 或 Java）兼容，提供存有大量可自定义“包”（即计算问题的解决方案）的大型存储仓库。这种开源包是基于编码方法的核心。此外，R 和 Python 允许将数据分析的所有步骤（即数据创建、整理、分析、解释和可视化）组合到同一工作流和文件中，例如，计算性笔记。计算性笔记是一种特定格式，它将分析工作流、底层代码及对其的描述，组合在一个可复现、可分发的文件中 [72]。在过去 10 年中，R 和 Python 整合了越来越多的处理地理信息的功能。它们现在形成了传统地理信息软件（geographic information system, GIS） 的合适替代品。波音（Boeing）和阿里巴斯—贝尔（Arribas-Bel）[72] 为地理空间数据分析提供了这样的计算性笔记示例。这种方法的优点是显而易见的。科学家可以使他的整个分析工作流程，包括使用的数据，都可以被公开访问。这使得其他研究人员不仅可以复制、再现、验证分析，而且只需替换输入数据，就可以毫不费力地将相同的分析应用于新的案例研究之中。

这种可复制性和可再现性是科学知识生产的关键支柱。能够独立再现实验结果是验证和确认科学发现的核心机制。它减少了不确定性、不一致性、出现错误结果的可能性。如果没有可复现性，正如卡尔·波普尔（Karl Popper）[73] 在他的著作《研究逻辑》中所强调的那样，实验结果可能是“对科学没有意义的单一事件”。尽管自 20 世纪中叶以来，可复制性和可复现性一直都是关键支柱，但它们的重要性已因复制危机被凸显出来。复制危机 [74] 于 2012 年首次出现，其对过去的发现和当前的科学研究成果产生了根本性的影响。这场危机是由心理学领域难以复制的研究成果引发的。这些研究成果先前已被认为是既定知识。对行为启动——即因外部暴露而导致我们的行为对潜意识的影响——长期持有的信念，突然因研究成果缺乏可复制性而受到了质疑 [75]。在包括医学和经济学在内的许多科学领域也发现了类似的问题。

人们越来越意识到了解实际根本原因——而不是关联——对于观察得到效果的作用。由安格瑞斯特（Angrist）和皮施克（Pischke）[76] 推广，用于衡量因果关系的定量方法，在各科学领域（例如计算机、社会、经济和政治科学、流行病学）中变得更加普遍。因果推理，即确定现象的独立实际影响的统计方法很难执行，城市研究分析尤其如此。尤其是实验成本过高、伦理问题或必要信息无法获取等情况下，许多使用因果推理方法的研究人员采用准实验研究

设计，试图复制实验条件。这是城市研究人员都非常熟悉的情况。准实验研究设计的一个实例，通常被称为最早的因果推理应用之一，是1854年伦敦流行病中约翰·斯诺（John Snow）的霍乱病例[77]。空间句法研究中许多概念的有效性已通过相关性分析被反复证明。然而，获得因果关系的证据，仍然是该领域的一个关键目标。麦科马克（McCormack）等人[78]强调了这样的一个应用案例，他们认为空间句法指标可能在进行建成环境和人类活动之间的因果推论方面发挥着关键作用。

空间句法领域已开始响应这些发展，例如，提供Space Syntax OpenMapping[79]，英国的预处理空间网络模型；公开主要工具的源代码（例如，depthmapX、PST for QGIS及QGIS的空间语法工具包）；引入rdepthmap[31]，一个基于R语言的实现depthmapX和R相互关联的包。但是，现有的工作流程仍然需要图形用户界面，安装附加软件或插件，并没有原生移植到R或Python。分析和生成可视化结果仍然是十分耗时的任务——尤其是在需要迭代的时候，因为在城市设计领域这是经常出现的情况。这样的R或Python包不仅使工作变得流程化，还能使该领域更容易被相关学科所介入。此外，如果模型大小在未来继续增加，被实现的算法变得过时，需要被更新或重新开发。富奇金娜（Fuchkina）等人针对可视图分析曾经描述过其可能实现的方式[80]，但仍需要进一步的工作。目前很少有将数据科学方法融入空间句法研究的尝试，但是在过去2年内有所增加[81-86]。这些研究都很充分地利用了现有的数据科学方法。然而，在全新数据科学方法与空间句法基本原理结合的过程中所产生的问题尚未得到解决。实验室和现场实验也很少，但准实验研究设计仍然是该领域尚未挖掘的机会。

5 结　论

综上所述，空间句法领域已进入应用扩展和整合阶段。活跃研究人员的数量和国际空间句法研讨会的研究成果数量正在稳步增加。方法和理论在世界范围内得到广泛接受并应用于跨学科的各种研究。然而，研究发展的主要动力仍来自于该领域内部。同时，理论和概念的新颖性较为缺乏，方法论的产出速度逐步放缓。新的计算方法，如机器学习和人工智能，尚未被接受。开放科学、可复制性和可再现性的趋势也只是逐步得到认可。使用准实验的研究设计的机会仍尚待挖掘，目前迫切需要建模和分析方法惯例的发展。

鉴于这些观察，我建议专注于以下发展重点。空间句法研究界需要接受在其他领域取得的方法论发展，并实施开放科学原则，包括：① 开发基于R及Python的定制包，以用于空间句法研究的模型创建、分析、和可视化；② 通过并行或动态图算法开发出更快的计算方法；③ 定义好清晰的建模惯例和标准化的报告方式（例如使用的模型类型、指标、概念和定义）；④ 增加被使用数据集的可访问性，例如，引入模型库和数据库；⑤ 引入计算性笔记，以实现实验结果的透明性、可访问、可复现；⑥ 更好地理解和融合个体行为机制，以开发新的路线决策模型（包括结合人类路径的不对称性等最新发现）；⑦ 专注于因果推理的研究设计，包括现场和准实验（其中包括测试和验证现有概念和理论）。

空间句法研究界需要重新回到其理论发展阶段，将精力集中在紧迫的社会问题上，并在此过程中加强与其他领域的合作，包括① 气候危机问题，例如解决空气污染，减缓海平面上升和极端天气现象，或解决粮食不安全问题；② 健康不平等问题，例如非传染性疾病、在受冲突影响和脆弱环境中有效提供护理以及缓解全球新冠大流行；③ 社会政治不平等，例如收入不平等或技术差距；④ 对边缘群体的包容（从广义空间句法模型转变为更好地理解和模拟个人行为），例如，妇女和女孩、少数民族、身心残疾的人、女同性恋、男同性恋、双性恋、跨性别、酷儿、双性人和无性恋者（LGBTQIA+）。

空间句法为建筑、城市设计和规划领域带来了新的科学标准。现在，该领域必须专注于保持这种早期驱动力并更深地参与到此类流程之中。

注释

Notes

1 参考2022年8月6日Google Scholar的结果。
2 选择度指标是在《空间布局，在城市尺度上使用密度》[16]一文中首次得到概述。
3 角度分析是在一本关于方法论的手册[20]中首次被提及。
4 研讨会的所有记录可查看：https://vimeo.com/showcase/8991882。
5 不同于空间句法分析，这些计算是基于原始图进行计算的。
6 也被称作地理数据科学。

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Developments in Space Syntax: Past, Present and Future

Kimon Krenz

1 Introduction

Over the last 50 years, the field of space syntax has evolved into a comprehensive theoretical and methodological framework for the investigation of the reciprocal relationship between space and society. Introduced by Bill Hillier (1937–2019) and his colleagues at the Bartlett, University College London, in the early 1970s, space syntax has grown into a large and diverse international research field. Since 1997, researchers from around the world meet at the bi-annual International Space Syntax Symposium with increasing contributions from adjacent fields. Today, the approach is applied in practice across the world with projects ranging from small-scale architectural interventions to country-wide strategic master plans. Evidence from space syntax research has widened our understanding of the fundamental functioning of cities and the spaces within them.

Since its inception, the field underwent a series of critical developments characterised by the introduction of core theoretical and methodological concepts as well as scientific methods and tools to test them. Most notably, however, is the notion of *spatial configuration*, which defineds space as a relational entity. This analytical concept reshaped the way research questions could be framed, i.e., through a space-first perspective. It allowed for the systematic quantitative description and comparison of complex spatial arrangements, such as floor plans, neighbourhoods, or cities and subsequently linking these spatial patterns to human activity. Underpinning was the realisation that any human action is taking place in physical space. In doing so such action leaves traces which ultimately shapes the very physical space itself and in turn influences future human actions[1]. Utilising the spatial configuration, Hillier and his colleagues were able to demonstrate that space is not a by-product of society, nor the sole background for human action, but an active driver in the way society constructs and reproduces itself over time[2].

Space syntax brought novel quantitative

scientific thinking to the discipline of architecture and urban design. It also revived a strand of research in the field of geography, i.e., 'locational analysis' that ceased to be of greater importance in the 1960s, partly caused by concerns about environmental determinism. Space syntax solved this dilemma by shifting the focus from determinism to human potential. Since its introduction, the notion of *spatial configuration* has led to a plethora of new concepts and the advancement of existing ones. The theoretical and methodological framework evolved heterogeneously and at such a pace that particular care needs to be taken when comparing evidence across past studies that investigate the same phenomenon.

In addition, the last decade has seen the increasing use of quantitative and computational methods in the fields of architecture, urban design, planning and geography. The growing recognition of the built environment as a contributing factor to social, economic and environmental inequalities has highlighted the need for better evidence and therefore reproducible objective methods for the quantification, evaluation and comparison of the physical space of cities. While space syntax has been at the forefront of these developments for many years, adjacent disciplines are increasingly incorporating and advancing such thinking. This trend has been accelerated by the ever-expanding accessibility of open data and the emergence of spatial data science methods, which brought forth a multitude of different quantitative approaches aiming to fill this methodological gap. The increasing availability of such alternative open-source spatial analytical tools, the emerging concentration on reproducibility and replicability, as well as the increasing focus on causal reasoning across sciences pose exciting opportunities for the field of space syntax, but also the need for methodological (re-) development.

In light of these developments, it appears to be an appropriate moment to reflect on past and present trajectories in the field of space syntax, in order to draw insights into likely trajectories as well as potentials. The aims of this paper are, hence, twofold i) to provide an overview of developments in the field of space syntax, and ii) to provide an outlook of opportunities and potentials for the field. Specifically, I will start with a review and classification of key space syntax publications to identify evolutionary stages. This is followed by insights into the theoretical production within the field using the results of a quantitative text analysis of conference proceedings presented at International Space Syntax Symposia. Furthermore, a review of cutting-edge research presented at the Space Syntax Lab Seminars, as well as emerging research from the 1st International Online Space Syntax PhD conference will be used to outline the present development. Finally, I will use these insights in combination with critical developments in the sciences as a whole to outline development suggestions for the field of space syntax.

2 Past Developments

Since its inception in the early 1970s, space syntax theory and methods have constantly been invented, extended, and refined. In addition, the approach addresses a large array of subfields of different spatial scales. This complexity elucidates the difficulties to define the field as a whole at a given moment in time. However, a look at key space syntax publications, identified through the introduction of key concepts as well as the frequency of a publication's citation, the release of analytical tools as well as key events can shed light on core evolutionary stages. In doing so, the evolution of the field of space syntax can be divided into three core stages, i.e., i) *theoretical development*, ii) *methodological advancements*, and iii) *extension and application* (Figure 1). These core stages are not clearly demarcated, but rather blur into one another. It is also worth noting that similar characteristics occur in all stages, albeit to varying degrees. Furthermore, the selected publications do not constitute a complete representation of the field, and instead should be seen as an attempt to distil and represent the scientific production of numerous researchers across the world. The subsequent sections will outline the characteristics of each evolutionary stage.

2.1 Theoretical development

The first evolutionary stage of the field can be characterised as *theoretical development* lasting from 1970 to 1999. Most of space syntax' fundamental theories and concepts were articulated during this period by Hillier and his colleagues at the Bartlett. This includes the three most cited[1] publications of the field as a whole, i.e., 'The Social Logic of Space' [3] (cited 9,625 times), 'Natural Movement' [4] (cited 2,283 times) and 'Space is the Machine' [5] (cited 6292 times). In addition, this period brought forth key publications such as 'Space Syntax'[6], 'Domestic Space Organisation' [7], 'Creating Life' [8], 'Ideas are in Things' [9], 'Finding the building in wayfinding' [10], 'Decoding Homes and Houses' [11] but also works that influenced them such as Michael Benedikt's 'Isovists and Isovist Fields'[12]. By looking at three selected publications relevant to the field of urban design, I will argue that the *theoretical development* stage was crucial for the field as it lay out three things a) it provided the methodological basis for the scientific investigation of the built environment and the space-society relationship, b) it introduced the theoretical concepts and their interpretation for the way society inscribes itself in space, and c) it identified key mechanisms that are fundamental for our understanding of the functioning of urban space and cities. The end of this period falls roughly around 1997, at the time of the 1st International Space Syntax Symposium, which functioned as an important impetus for the subsequent progress of the field.

Space syntax was first mentioned in the homonymous landmark publication by Hillier et al[6]. The paper is influenced and preceded by a series of publications by Hillier and his colleagues, Adrian Leaman, John Musgrove and others, such as 'Knowledge and Design' [13] or 'the Man-environment Paradigm'[14] in the early 1970s. These publications constitute an important primer as they pathed the way for a scientific research programme investigating the built environment. In 'Space Syntax' Hillier and his colleagues were concerned with "how and why different societies produce different spatial orders through building forms and settlement patterns[6]", for this, they proposed to describe and analyse relationships in spatial arrangements through mathematical representations. They then linked these representations to information on the inhabitants' use in order to extract insights into the societies that shaped them. The important proposition here is that space has a syntax, a set of combinatory rules that form patterns, which in turn can carry meaning. By understanding the syntax of spaces, Hillier et al. suggested, we might be able to say something about the people that inhabit them. 'Space syntax' outlined the fundamentals for a space-first investigation into space-society relationships. Hillier later explained, 'Space Syntax' "… was the first paper that suggested you could study architectural space in a scientific way[15]".

8 years later, in 1984, Hillier and Hanson published their seminal book 'The Social Logic of Space'. The book introduced a novel spatio-social theory, supported by historical anthropological, archaeological, and ethnographic data. Hillier and Hanson took forward the initial ideas expressed in 'Space Syntax' and developed them into a set of systematic methods. Specifically, they proposed to describe spatial patterns through graph representation. They further demonstrate how these methods can provide crucial insights into how social rules and hierarchies are embedded into space, using a series of exemplary spatial arrangements at varying scales from small individual spaces to village settlements. In doing so, they captured a fundamental function of urban space, i.e., emergence. Urban space, Hillier and Hanson argued, is created and shaped by individuals over time without an overarching idea of a global structure, yet small-scale changes can have an emergent effect on the global pattern. A pivotal characteristic that enables to study space in its own right. In addition, 'The Social Logic of Space' introduced a series of concepts rooted in social theory (e.g., *description retrieval*, *spatial–transpatial*, *genotypes–phenotypes*[3]), as well as methodological concepts (e.g., *axial line*, *convex space*, *integration*, *global–local*[3]) that enable investigations into the space–society relationship.

In 1996, Hillier published his masterpiece 'Space is the Machine'. In this work, he builds on 'The Social Logic of Space', particularly the concept of *spatial configuration*, as well as the theoretical and methodological developments made since its first edition. Notably, these preceding publications include works such as 'Creating Life'[8] which added the concept of *choice*[2][16] and *intelligibility*, or 'Natural Movement'[4] which introduced the homonymous concept that describes the share of the pedestrian movement that is determined by the spatial configuration itself–a crucial mechanism shaping the potential of urban space. In a multitude of examples, Hillier demonstrates how the *spatial configuration* is the pivotal mechanism through which the built environment governs everyday life[5]. Using concepts such as *co-presence*[5] and *co-awareness*[5], Hillier further elaborates on the implications of the potentials provided by the *spatial configuration* on social cohesion. Just like in 'The Socal Logic of Space', 'Space is the Machine' presents not only the analytical tools but extended the framework of socio-spatial notions for the interpretation and description of their results. By providing analytical methods and concepts for their description, Hillier effectively overcame the issue of *non-discursivity* of space[5]. Utilising the growing computational opportunities in the early 1990s, 'Space is the Machine' also presented novel ways of applying the graph theoretical measures to larger spatial arrangements and entire cities and presented these in a series of insightful cartographic visualisations–which up to this date make space syntax analyses and their rainbow colour symbology indistinguishable.

2.2 Methodological Advancement

The second evolutionary stage of the field took place from 1999 to 2010 and comprises critical *methodological advancements*. Space syntax has always been characterised by a close linkage between theory building and methodological/analytical developments. Nevertheless, this period is particularly representative for its methodological progress. Substantial achievements have been made in computational methods and the creation of tools for the application of space syntax to complex and city-wide systems. The focus on the theoretical development of earlier years shifted towards an *intensified development* of new methods to explore the relationship between the built environment and human movement behaviour. While theoretical production continued, with key publications such 'Centrality as a Process'[17], 'Network and Psychological Effects'[18], or 'The City as One Thing'[1], the period was particularly characterised by methodological work such as 'From Isovists to Visibility Graph'[19], 'Angular Analysis' [3][20-21], 'Space Syntax-based Agent Simulation'[22], 'From Axial to Road-Centre Lines'[23], and 'Space, Density and Urban Form'[24].

It is at this time that collaborations with computer scientists such as Alasdair Turner (1969–2011) or Nick Dalton among others resulted in tailored software and algorithmic solutions for the analysis of the built environment and simulation of human behaviour. These experimental and simulation-based computational approaches were used as tools to "thinking with"[2] and deepened our insights into human behaviour (see, e.g., the work of Ruth Dalton [25]). This included–among others–applications such as *OmniVista*[26] a tool for Isovist fields and path analysis, or the first version of *Depthmap*[27] a tool for visibility graph analysis (VGA)[19]. The development of *Depthmap* continued through the years and included additional capabilities such *as convex space* and *axial line analysis, angular segment analysis*[21] and agent-based simulations[22]. The introduction of *angular segment analysis* led not only to improvements in the modelling of human movement flows but also to insights into the mechanism of the human route choice decision-making[18]. Until today, *Depthmap* is still the base for space syntax analyses of many researchers across the world. Shortly after, Ståhle, Marcus and Karlström presented the *Place Syntax Tool* which combines principles of attraction models with the space syntax-based configurational approach[28]. Ståhle et al.'s tool was fully integrated into geographic information systems (GIS) which opened up streamlined workflows and easier incorporation of the growing availability of locational information.

It is also during this period that large-scale data sets of vector-based geographic information became available. The field of space syntax, was an early adopter of such data in urban analyses–not only on a technical level (as in the *Place Syntax Tool* or *Depthmap*) but driven by theoretical considerations, which is a critical distinction to alternative approaches of urban modelling (such as in the novel field of *urban analytics*) which exists until now. For example, Turner[23] proposed and tested the incorporation of the so-called road-centre line data, a data type that by now forms the basis for every contemporary routing application. The application of road-centre line data has found ample support in the community, due to its large-scale availability in the form of volunteered geographic information or governmental data sources.

The end of the *methodological advancement* stage falls within the years around the publication of the first issue of the *Journal of Space Syntax* (JOSS)[29]. JOSS' introduced a dedicated place for the publication of theoretical and methodological progress in space syntax and was an important milestone for the field.

2.3 Extension and Application

The third and ongoing evolutionary stage started in 2010 and might be best described by an increasing *extension and application* of the methodology. Whereas previous evolutionary stages provided fundamental theoretical and methodological novelty, the *extension and application* stage is characterised by thematic

diversification, the widespread usage of space syntax in various fields and case studies, as well as increasing open access to methods and tools. The magnitude of the growth of the field can be approximated by looking at the usage of the bigram 'space syntax' within all books published predominantly in the English language (Figure 2). After 2010, we can observe a steep increase in the term space syntax, which developed comparably to the term urban morphology. The last decade has seen a predominant growth in contributions and applications of space syntax across the world. This is in part driven by the global success of the approach, as well as efforts to make the tools and algorithms openly accessible. Important markers for this development are the releases of a series of open-source space syntax applications. For example, *dephtmapX* (a ported version of *Depthmap* available for Linux, OSX and Windows) by Tasos Varoudis in 2012, the *Space Syntax Toolkit for QGIS*[30], the R package *rdepthmap*[31], or the *Place Syntax Tool for QGIS*[32].

Such open-source software provides a series of benefits for the research community as a whole. This includes free and open access to the software and its code, faster identification and fixing of bugs, closer proximity to the user base and direct feedback loops, opportunities for the community to become active developers (i.e., freely examine, modify, and redistribute the software), transparency and openness regarding the functionality of algorithms and their implementation, and availability of accompanying handbooks. Each of these benefits plays a role in the widespread adaptation of open-source software such as *depthmapX*. The increasing availability of methods, tools and data has also led to applications of space syntax methods to ever-increasing scales from metropolitan[33], sub-regional[34], regional, to country-wide[36], which–among other things–also highlighted the computational limits of existing space syntax algorithms for the calculation of network centralities.

However, the growth of the community and the increased accessibility of tools do not come without challenges for the field. There are increasing inconsistencies across different applications in terms of the construction of models[37, 38], the calculation of metrics and the implementation of algorithms. A challenge that has been highlighted by Sharmin and Kamruzzaman[39] at the example of existing research into the relationships between space syntax measures and pedestrian movement. This is also visible in the number of authors that have addressed the challenge of developing generalisable methods for the creation of a road-centre line-based space syntax models[40-43].

Simultaneously, neither theoretical nor methodological advances have stopped during this time, see, e.g., the introduction of *normalised least angular choice*[44], the release of sDNA[45], *DeCodingSpaces Toolbox*[46], or most recently the *Isovist App*[47] to name only some. Furthermore, several former PhD students and researchers from the field have published books by taking principles and notions of the space syntax approach and extending and applying these to a variety of topics, e.g., urban and building-based research agendas[48, 49], the role of space for society[50-53], literature, narrative and imagination[54-56], or a specific research field such as health care design[57]. In addition and critical for the growth of the field, several authors have outlined space syntax teaching curriculums[58, 59], with the most comprehensive work recently published by van Nes and Yamu[60].

In many ways, the *extension and application* stage can be seen as a process of consolidation. As it has been noted by Karimi[61], today "space syntax research cannot be considered a specialized or novel field anymore", instead the widespread application of space syntax theory and methods points toward a general acceptance of the approach in adjacent disciplines. However, most of the cross-disciplinary research is driven from within the field of space syntax, rather than being initiated from adjacent disciplines (this might be in part due to the arguably overwhelming set of concepts or potential inconsistencies between existing studies). The extent of this process becomes apparent with a view to the variety of fields in which space syntax research has been applied (Figure 3).

2.4 Space Syntax Symposia and Conceptual Trajectories

The biggest evidence of the growth and application of the field, however, is the biannual International Space Syntax Symposium. Since 1997, 13 international symposia have taken place in the UK, Brazil, USA, the Netherlands, Turkey, Sweden, Chile, South Korea, Portugal, China and Norway. Over this time, the research community has produced over 1,500 peer-reviewed conference proceedings (Figure 4, left) a large body of more than 6,000,000 written words. This includes work from over 1,100 authors and co-authors from over 50 different countries. Conferences and symposia are central places to understand the scientific production of a research field. They constitute the forum at which researchers meet in person to present, discuss and test new ideas and findings. These are often recorded in conference proceedings, which in aggregation, can provide a window into past, present and ongoing developments of a field. Due to the regular frequency, space syntax conference proceedings provide consistent temporal insights into the development of this field. By investigating quantitatively how specific terms are used within the text one can deduct insights into the scientific production.

In 2019, Krenz et al. presented the results of such a quantitative text analysis at the 12th International Space Syntax Symposium (ISSS). They used the text body of all conference proceedings presented at the ISSS between its inception and 2017, and analysed the frequency and co-occurrence of concepts over time. In doing so, they have created a network of connected concepts and estimated the trajectories of their usage. Their analysis showed that related concepts constitute clusters within the network and that these clusters feature differing trajectories[62]. Most notably, it was the observation that concepts rooted in social theory (e.g., *social solidarity*, or *description retrieval*) declinigly used in the field. Simultaneously, there was an increasing trend in the use of methodological concepts–particularly the use of *network-based centralities, segment angular analyses* and related concepts, with the exception of concepts related to *axial line analysis* (e.g., *global to local*, or *intelligibility*) which are declining. A cluster formed of building-based *visibility graph analysis* and *Isovist analysis* showed heterogeneous trajectories, pointing towards ongoing developments at the building scale. In addition, the number of newly emerged concepts per conference year decreased consistently over the years constituting a decline in conceptual novelty (Figure 4, right). This can also point towards a general consolidation of the field, where proposed concepts are accepted as established and tested methods. The authors conclude that there has been a 'technological turn' within the field[62], describing a shift from theoretical production toward technological progress. This observation affirms the identified developmental stages. This process of increasingly incorporating computational methods is also observable across all sciences.

In summary, the field of space syntax shows consistent growth over time. The past developments in the field can be grouped into three broader evolutionary stages, characterised by an early theoretical production, followed by the intensified proposition of methods, and an extension stage of increasing usage of the approach across the world. There is a decline in theoretical production and conceptual novelty and use of concepts rooted in social theory apparent, which is accompanied by an increasing methodological application.

3 Present Developments

In addition to the past developments, a look into ongoing activities within the field, as well as early career research can provide insights into present developments and their influence on future research. For this, I will take a look at the contributions to the 1st International Online Space Syntax PhD conference, as well as cutting-edge research presented at the Space Syntax Lab Seminars. This will provide insights into the thematic focus of current scientific production in the field of space syntax.

The growth of the field has brought up the opportunity for the introduction of the 1st International Online Space Syntax PhD conference. The proposition of the PhD conference was also motivated by the COVID-19 pandemic-imposed postponement of the International Space Syntax Symposium and the need to provide a forum for the ongoing research of PhD students in the field. Initiated by the international space syntax steering committee's interim executive committee represented by Akkelies van Nes (Western Norway University of Applied Sciences), Meta Berghauser Pont (Chalmers University of Technology, and Laura Vaughan (University College London), the conference attracted contributions from 41 PhD students whose research involves the application of space syntax theories and methods[63]. A look at the thematic range of these contributions can provide a proxy for research outputs and the likely contributions in the future. This becomes apparent by noting that 18 of these 41 PhD students have also presented their work at the 13th International Space Syntax Symposium the following year, indicating that an upcoming generation is on the way to establishing themselves as researchers in the field of space syntax.

Broadly, the work of these postgraduate researchers falls into the seven thematic groups, i.e., *transport, social and political spaces*, *morphology*, *complex buildings*, *heritage and archaeology*, *green space*, and *urban space*. Each of these thematic groups features a variety of work and subgroups. Most contributions fall into the group of *urban space*. This includes projects that are focused on urban space at various scales, particularly suburban and peripheral areas, microeconomic activity (e.g., town centres, retail and land-use activities), as well as investigations into the phenomenon of co-presence. Noteworthy in this group is the work of Yufeng Yang, who sheds light on the impact of gated and non-gated housing areas on community cohesion in Wuhan, China[63]. The second largest group is that of *complex buildings*, containing projects investigating various building-level phenomena (e.g., wayfinding and building-street interfaces) and complex building typologies (e.g., museum and exhibition spaces, schools and educational environments, workplaces, as well as hospital and care environments). Exemplary of this strand of research is the work of Chrystala Psathiti who assesses educational environments in lower secondary school buildings in Cyprus using a temporal socio-spatial approach[63]. The thematic group of *transport* covers topics within the field of transport planning which has a long tradition in space syntax research. Work ranges from investigations into pedestrian movement, cycling infrastructures, and modal splits to novel approaches for modelling combined transport networks. Particularly the work of Po Nien Chen on multilevel multimodal network modelling constitutes a promising contribution to the field[63]. The work within the group of *social and political spaces* focuses on the spatial realities and implications of social and political policies. These features important contributions to timely topics such as crime, ethnic diversity and segregation, gender differences, as well as social housing. Michael Livesey's work is worth mentioning in this context. He investigates how the 'criminalisation' policy of the British Government in the mid-1970s is expressed in urban areas and prison designs in Northern Ireland[63]. The work in the thematic group of *heritage and archaeology* is predominantly concerned with data generation for archaeological research, the history of public space and culturally led pedestrian movement as tools for heritage efforts. Noteworthy here is Paulina Konarzewska's work dealing with the acquisition of historic road networks for application in the archaeological research field[63]. Contributions of the thematic group of *morphology*, contain work on the geometric property of cities, particularly coastal towns, as well as pattern languages. Exemplary of these investigations is the work of Mauricio Pereira Martins who looked into peri-urban centralities on the edges of coastal towns[63]. Finally, an increasing number of graduate researchers are focusing their work on *green space*. This comprises work on methods for the description of spatial properties (e.g., degree of enclosure), but also methods for the development of networks of green spaces. Rina Magen's work, e.g., investigate spatial properties of neighbourhood parks and boulevards in the Tel-Aviv metropolitan area, Israel[63].

The Space Syntax Lab Seminars[4] bring together researchers and students to share their work at the intersection of architecture, urban space and society. Organised by The Bartlett's internationally renowned Space Syntax Laboratory, the series features a mixture of international invited speakers, UCL researchers and PhD students providing diverse viewpoints on how we understand, analyse and design both buildings and cities. Throughout the last year, the online seminar hosted eleven different international speakers attracting more than 1100 participants from 80 different countries. Speakers included, e.g., Zhang and Chiaradia[64] who showed how the use of 3D information in angular analysis can improve the prediction of pedestrian flows, Fredrick and Vennarucci[65] who presented a novel archaeological research methodology combining 3D virtual reality methods with space syntax network analyses to explore the role of the roman house, Martin Bielik[66] who presented a method to disentangle the contribution of the configuration and attractors to pedestrian movement, Constance Desenfant who elaborated on how the built environment can influence women's navigation and perception of safety, Paolo Santi[67] who presented an alternative approach for route-decision making based on a vector-based directional shortest path, or Simons[68] whose work is bridging urban morphology approaches with machine learning methods to detect and predict urban archetypes at pedestrian scales. The seminars have demonstrated how current research covers a large thematic variety, but also how adjacent quantitative fields increasingly incorporate and extend fundamental

ideas from space syntax.

Overall, the examples of doctoral projects and cutting-edge research show that thematic diversity is distinctive for the field of space syntax (compare Figure 3). They highlight how existing methods are increasingly applied to adjacent disciplines. However, only few are addressing pressing societal issues, such as the climate crisis, health, social or political inequalities, or discrimination and marginalization. The projects exhibit little methodological novelty compared to the *methodological advancements* stage during the early 2000s. In addition, the incorporation of fundamental ideas of space syntax in adjacent disciplines brings ample opportunities for methodological developments. Space syntax methods are grounded in theoretical considerations about human interaction, perception, cognition and experience, which is a particular quality of the approach as a whole. A lack of driving new methodological developments from within the field of space syntax, however, carries the risk of diminishing the importance of these theoretical foundations of space syntax. An example of this is the *OSMnx* tool developed by Boeing[69]. The tool provides a framework for the automated extraction of road-centre line data from volunteered geographic information (i.e., OpenStreetMap) and the analysis using–among others–graph-based centrality measures[5]. The tool is widely popular (cited 880[1] times) and applied in ground-breaking research[70] and research with global policy relevance[71]. One of the reasons for the wide-scale application of *OSMnx* is its open-source code-based framework, online documentation and easy implementation through the programming language Python. These properties will become increasingly important to be incorporated into future space syntax developments.

4 Trajectories in Scientific Production and Development Potentials for Space Syntax

In the following section, I will use three key trends prevalent across the sciences, namely, i) the increasing popularity of data science methods, ii) the drive to open science approaches, and iii) the aim to determine causality, to outline important directions relevant for the field of space syntax.

In the first decade of the 21st century people have experienced an exponential growth of information. Data collection has accelerated with the widespread availability and affordability of mobile devices, cameras, remote sensing, the internet of things and the increasing digitalisation of governmental and corporate administrative tasks. The result was the emergence of 'big data', i.e., data sets that become too large or complex for traditional computer software. Such structured and unstructured data sets provide ample opportunities to extract knowledge and behavioural patterns. By now, likely any human activity in virtual and physical space in the industrialised world leaves digital traces and contributes to a pool of information capturing human behaviour on a societal level. Simultaneously, the development of tools and methods to mine and analyses such data sets has exploded. Combined these tools, methods, processes and algorithms form the interdisciplinary field of *data science* and its adjacent and incorporated fields of *artificial intelligence* and *machine learning*. The extent of this development becomes clearer when comparing the occurrence of the bigrams 'space syntax', 'urban analytics', 'city science', and 'urban morphology' to 'data science' and 'machine learning' (Figure 5). Compared to the term 'space syntax', 'data science' is used 10.96 times and 'machine learning' 22.38 times more frequently. With the increasing incorporation of data science methods across all scientific fields, this development is very likely to continue.

In addition, an emerging subset of data science is *spatial data science*[6], which incorporates the unique properties of spatial data in the analysis. Fundamental to the field of spatial data science is that novel methods and tools are tailored to include space not as generic variables, but to utilise its properties, e.g., location, distance, relationship or interaction, as the basis for the analysis. The need for these novel methods has been brought forth by the growing availability of spatio-temporal information, generated by increasing mapping efforts (e.g., OpenStreetMap, or satellite-based aerial imagery), the collection of precise geolocations (e.g., through GPS tracking of mobile phones, fitness equipment, or actively shared on social media), and the geo-referencing of existing information. One contributing factor to the success of (spatial) data science methods, besides the outlined qualities in dealing with questions surrounding (spatial) big data, is their accessibility, reproducibility and open science approach. Accelerated by the COVID-19 pandemic, there is an increasing demand for open science approaches by governments and academics. This entails not only open and accessible tools and methods, but reproducible workflows, datasets and computational environments.

One form of achieving such an open science approach is through the use of open programming languages (e.g., *R* or *Python*) and computational notebooks. Both *R* and *Python*, are particularly popular among data scientists because they are platform-independent languages, compatible with other programming languages (e.g., C, C++ or Java) and provide a large repository of existing 'packages' (i.e., solutions for computational problems) that can be customised. Such open-source packages are the core of coding-based approaches. In addition, *R* and *Python* allow combining all steps of the data analysis (i.e., data creation, wrangling, analysis, interpretation and visualisation) into a single workflow and file, e.g., a computational notebook. Computational notebooks are a specific format that combines analytics workflows, underlying code, and their description in a single reproducible and distributable file[72]. Over the last decade, *R* and *Python* have increasingly incorporated capabilities to deal with geographic information. They now form legitimate alternatives to traditional geographic information software (GIS). Boeing and Arribas-Bel have provided an example of using such computational notebooks for geospatial data analyses[72]. The advantages of such an approach are obvious, a scientist can make his entire analysis workflow, including the used data, publicly accessible. This allows other researchers not only to replicate, reproduce and verify the analysis but also with little effort to apply the same analysis to new case studies by merely exchanging the input data.

Such replication and reproducibility are key pillars of scientific knowledge production. Being able to independently reproduce observations is the core mechanism through which scientific discoveries are validated and confirmed. It not only reduces uncertainties, inconsistencies and the likelihood of erroneous findings, but without reproducibility, observations are potentially "single occurrences … of no significance to science" as Karl Popper[73] stressed in his book *Logik der Forschung*. Albeit being key pillars since the mid-20th century, the importance of replication and reproducibility has been brought to the fore by the *replication crisis.* First coined in 2012, the

replication crisis[74] had a fundamental impact on past findings and the present scientific research production. The crisis was triggered by the difficulty of replicating findings in the field of psychology that were considered established knowledge. Long-held beliefs such as on behavioural priming, i.e., the subconscious influence of our behaviour through external exposures, have suddenly been put into question by the lack of successful replication of findings[75]. Similar concerns have been identified in many scientific fields including medicine and economics.

There is increasing awareness of the role of understanding the actual underlying cause, as opposed to an association, for an observed effect. Popularised by Angrist and Pischke[76], quantitative approaches for measuring causation have become more prevalent across a large variety of scientific fields (e.g., computer, social, economic and political sciences, or epidemiology). Causal inference, the statistical approach to determining the independent actual effect of a phenomenon, is difficult to perform and this is the case for analyses in urban research particularly. Many researchers using causal inference methods employ quasi-experimental research designs, in an attempt to replicate experimental conditions. This is particularly the case that the cost of conducting experiments, ethical concerns, or access to necessary information is prohibitive. It is the situation that all urban researchers are very familiar with. An example of a quasi-experimental research design and often referred to as one of the earliest causal inference applications is John Snow's cholera cases in the London epidemic of 1854[77]. The validity of many of the concepts in space syntax research has repeatedly been demonstrated through correlational analyses. Evidence for causal relationships, however, remains a crucial objective for the field. An exemplary application has been highlighted by McCormack et al. who argue that space syntax metrics might play a pivotal role in informing causal inferences between the built environment and physical activities[78].

The field of space syntax has started to respond to these developments, e.g., by providing *Space Syntax OpenMapping*[79], a pre-processed spatial network model of Great Britain, by making the source-code of main tools openly accessible (e.g., *depthmapX*, *PST for QGIS*, or *Space Syntax Toolkit for QGIS*), or through the introduction of *rdepthmap*[31] an R-based package providing a connection between *depthmapX* and *R*. However, the existing workflows still require a graphical user interface, the installation of additional software or plugins, and are not natively ported to *R* or *Python*. Conducting an analysis and producing visual results is still a time-consuming task–particularly when iterations are required, as it is often the case within the field of urban design. Such *R* or *Python* packages would not only streamline workflows but would make the field substantially more accessible to adjacent disciplines. Furthermore, the implemented algorithms are becoming dated and need either updating or fundamental redevelopment if model sizes are increasing in the future. A proposition on how this might look like has been made by Fuchkina et al. for the visibility graph analysis but further work is needed[80]. Only few attempts have been made to incorporate data science methods into space syntax research, albeit increasing during the last 2 years[81-86]. These studies make largely use of existing data science methods. The opportunity to incorporate fundamental space syntax principles in novel data science approaches, however, has yet to be addressed. There are also few lab and field experiments, but the use of quasi-experimental research designs remains an untapped opportunity for the field.

5 Conclusion

In conclusion, the field of space syntax has entered a phase of extended application and consolidation. The number of active researchers and contributions to the International Space Syntax Symposia is steadily increasing. Methods and theories are widely accepted and applied worldwide in various cross-disciplinary research; however, the main driver of engagement comes from within the field. Meanwhile, there is a lack of theoretical and conceptual novelty and methodological production has slowed. The use of novel computational methods, such as machine learning and artificial intelligence has yet to be embraced. Tendencies for open science, replicability and reproducibility are only slowly recognised. Research designs using quasi-experiments remain untapped opportunities. There is an urgent need for the development of modelling and analysis conventions.

In light of these observations, I recommend concentrating on the following developmental priorities:

Methodological Priorities

The space syntax research community needs to embrace the methodological progress made in other fields and implement open science principles. This includes focusing on 1) the development of tailored *R* or *Python*-based packages for the model creation, analysis and visualisation of space syntax research; 2) the development of faster computational methods through parallelised or dynamic graph algorithms; 3) the definition of clear modelling conventions and a standardised way of reporting (e.g., used model types, metrics, concepts, and definitions); 4) increasing the accessibility to used data sets, e.g., through the introduction of a model and data repository; 5) the introduction of computational workbooks for the purpose of transparent and accessible reproducibility; 6) the better understanding and incorporation of mechanisms of individual behaviour for the development of novel route decision-making models (incl. incorporating the latest findings on, e.g., asymmetries in human paths); and 7) the focus on causal inference research designs, including field and quasi-experiments (among others to test and validate existing concepts and theories).

Thematic Priorities

The space syntax research community needs to reconnect to its theoretical development stage, direct its efforts on pressing societal issues and increase collaboration with other fields in doing so. This includes tackling issues around 1) the *climate crisis*, e.g., tackling air pollution, mitigating rising sea levels and extreme weather phenomena, or addressing food insecurities; 2) *health inequalities*, e.g., noncommunicable diseases, effective provision of care in conflict-affected and vulnerable settings, and the mitigation of global pandemics; 3) *socio-political inequalities*, e.g., income inequalities or technological disparities; and 4) the *inclusion of marginalized groups* (moving from generalised space syntax models to better understand and model individual action), e.g., women and girls, ethnic minorities, people with physical and mental disabilities, or lesbian gay bisexual transgender queer intersex and asexual (LGBTQIA+) people.

Space Syntax brought new scientific standards to the field of architecture, urban design and planning. Now, Sholars and reseachers in the field must focus on maintaining this early drive and further engagement with such processes.