**中文摘要**

视觉系统感知和预测运动信息的认知和神经机制是心理学科的核心研究课题。视觉的产生式理论指出，视觉系统不仅感知信息本身，还对信息背后的潜在产生过程进行推理，并据此构建产生式表征指导后续认知活动。运动的产生过程涉及物理和心理两方面因素，对其共同作用的联合推理是视觉运动加工顺利进行的重要保障。因此，探明视觉系统的“物理-心理”联合推理机制，是理解视觉运动加工和视觉智能本质的核心。重力是日常生活中最普遍和重要的运动产生因素之一，探讨视觉运动加工中重力的表征及动态加工机制，是厘清视觉系统“物理-心理”联合推理机制的关键，既有助于完善视觉运动加工相关理论，也有助于揭示视觉系统对重力变化的动态适应过程，具有重要的理论意义和应用价值。

重力长期稳定作用于视觉运动加工情景中，难以用传统研究方法将其作用分离，故而难以在地面研究中直接考察重力改变对视觉运动加工的影响。空间站中能够提供真实的微重力环境，对空间站中航天员进行追踪研究，能够考察视觉系统适应微重力环境以及重新适应重力环境的全过程，从而完整、动态地揭示视觉运动加工对重力的适应机制，因此有必要在空间开展本研究。

围绕视觉运动加工机制这一科学问题，本项目形成以下关键科学目标：探明视觉系统感知和预测运动信息的过程中对重力的表征及其作用机理，探明视觉运动加工对重力变化的适应机制，并构建计算模型模拟重力环境变化下视觉运动加工的动态过程。

项目拟通过三部分研究，分别从基础运动感知、非生物运动预测和生物运动预测三方面以递进的思路展开对视觉运动加工过程的系统研究，通过行为实验测量个体加工视觉运动信息的绩效，通过眼动技术测量视觉运动加工中的信息选择过程，在此基础上借助认知建模方法构建计算模型对被试的认知过程进行模拟，并比较模型与人类在相同任务中表现模式的异同，以揭示视觉运动加工的潜在认知过程。同时通过对特定个体小样本数据的拟合，模型还能够作为特定个体的量化画像，或可用于针对特定个体的评估和预测。

**英文摘要**

The cognitive and neural mechanisms of visual system in perceiving, predicting, and reasoning about motion information are core research topics in psychology. The generative theory of vision suggests that the visual system not only perceives the motion information itself, but also infers about the potential generative process behind the motion, and constructs a generative representation to guide subsequent cognitive activities. The generation process of motion involves both physical and mental factors, and joint reasoning of their common effects is an important basis for the effective progress of visual motion processing. Therefore, exploring the "physical-mental" joint reasoning mechanism of the visual system is the core for understanding the nature of visual motion processing and visual intelligence. Gravity, as one of the most common and important factors in motion generation in daily life, has a universal impact on visual motion processing and may be internalized as human core knowledge, automatically influencing visual motion processing. Therefore, exploring the representation and dynamic processing mechanism of gravity in visual motion processing is the key to clarifying the "physical-mental" joint reasoning mechanism of the visual system, not only helps to improve visual motion processing related theories, but also reveals the dynamic adaptation process of the visual system to gravity changes, which has important theoretical and applied values.

Traditional research methods are difficult to isolate the effect of gravity due to its stable long-term action in visual motion processing scenarios. To directly examine the influence of gravity changes on visual motion processing, experiments should be done in microgravity environments. Tracking studies on astronauts in space stations can reveal the entire process of visual system adaptation to microgravity environments and re-adaptation to gravity environments, enabling a complete and dynamic understanding of the adaptation mechanism of visual motion processing to gravity. Therefore, it is necessary to carry out this study in space.

This project forms the following key scientific goals around the scientific problem of visual motion processing mechanisms: exploring the representation and mechanism of gravity in the process of visual system perception, prediction, and reasoning of motion information; revealing the adaptation mechanism of visual motion processing to gravity changes; and constructing computational models to simulate the dynamic processing of visual motion processing with gravity.

The project plans to conduct three experiments to systematically study visual motion processing from three aspects: basic motion perception, physical motion prediction, and social motion prediction. Behavioral experiments will be used to measure individual performance in processing visual motion information, eye movement technology will be used to measure information selection processes in visual motion processing. Moreover, cognitive modeling methods will be used to construct computational models to simulate the cognitive process of participants, and compare the differences and similarities between the model and human performance in the same task to reveal the potential cognitive processes of visual motion processing. At the same time, through fitting specific individual data, the model can also serve as a quantitative portrait of the specific individual and can be used for assessment and prediction of that individual.

The project plans to include six astronauts as the experimental group, and measure their motion processing before entering space, during space, and after returning to the ground. Among them, two measurements are planned during the 5th week and the 3rd week before entering space; four measurements are planned during the 1st week, 4th week, 8th week and 12th week after entering space; and two measurements are planned during the 1st week and 3rd week after returning to the ground. By comparing the performance differences of individuals in the same task at different time stages, the influence mechanism of gravity changes on visual motion processing and the individual adaptation mechanism to gravity changes can be revealed. In addition, for each experiment, conditions that are not expected to be affected by gravity changes will be set up. The differences between these conditions and the gravity-related conditions could help to eliminate factors other than gravity. The project also plans to recruit control group participants who are demographically similar to the experimental group, and perform multiple measurements at the same time as the experimental group but on the ground only. By comparing the task performance of the control group with the experimental group at different stages, factors related to time can be excluded.

In terms of engineering, the experimental procedures involved in this project will run, display, and collect data on laptop computers. Some experiments plan to collect eye movement simultaneously, which will require the use of laptop computers and eye movement devices already equipped in the space station. During the space orbit stage, astronauts will need to manipulate laptop computers and eye movement devices to complete behavioral and eye movement experiments. The experimental procedures are installed in advance on laptop computers. Experimental data will be automaticly recorded on laptop computers, and transmitted back to the ground at convenience.

一、研究意义和必要性

**研究意义**

人类所处的环境中充斥着大量运动信息，视觉系统对运动信息的感知和预测是人类与环境顺利交互的重要基础，相关认知机制一直是心理学科的核心研究领域之一。视觉领域的前沿研究揭示，人类的视觉系统以产生式的方式加工运动信息，即视觉系统不仅感知运动信息本身，还对运动背后的潜在产生过程进行推理，并据此构建产生式表征指导后续认知活动。**视觉系统如何构建和利用产生式表征，是视觉运动加工研究中的关键课题。**

运动的产生过程同时受物理环境和心理因素的影响，厘清视觉系统如何对物理-心理因素进行联合推理，是理解视觉运动加工和视觉智能本质的核心。重力是人类日常生活环境中所涉物理规则的典型，一方面，重力在整个地球表面相对稳定存在，同时作用于认知活动的主体（人）和客体（运动对象），对视觉运动加工产生普遍的影响；另一方面，重力在人类进化的漫长过程中相对稳定存在，极可能内化为人类先验的核心知识（core knowledge），对视觉运动加工产生自动化的影响。因此，探讨重力变化情景下视觉对运动信息产生式表征的构建和利用，既有助于揭示视觉运动加工中重力的表征，**推动完善视觉运动加工“物理-心理”联合推断理论**，也有助于揭示视觉系统对重力变化情景的动态适应过程，**为设计该情境下的人机交互系统和制定训练计划提供建议和指导**，具有重要的**理论意义和应用价值**。

**研究必要性**

* 环境中的运动对象和人类自身时常受到重力影响，在视觉运动加工中，重力最具代表性的物理因素。因此，**重力是研究视觉系统“物理-心理”联合推断机制的关键切入点，有必要探明其在视觉运动加工中的表征及动态加工机制**。
* 重力稳定作用于环境中的所有对象，难以用传统研究方法将其作用分离。以地面模拟为主的研究手段，并未从根本上改变重力的作用，而是引入了新的作用因素，综合产生失重体验，因而难以区分人类视觉系统是否改变了对重力的表征，或是通过叠加对其他因素的表征，产生失重状态下的视觉体验。**为直接、准确地考察视觉运动加工中对重力的表征及其作用，有必要在微重力环境下开展研究**。
* 重力长期作用于视觉运动加工情景中，极可能固化为人类先验的核心知识，仅在短暂环境变化状态下开展研究，难以捕捉视觉系统对该因素变化的适应过程。围绕长期处于微重力环境的航天员开展研究，有助于揭示视觉系统适应微重力环境以及重新适应重力环境的全过程。**为完整、动态地描绘视觉运动加工对重力的适应机制，有必要在地面-空间-地面开展追踪研究。**

二、国内外研究现状

人类所处的环境中存在大量运动对象，维持对外界的稳定认知和实现与外界的动态交互，依赖于对运动信息的有效加工。视觉系统在感知、预测和推理外界物体运动上展现出了强大的能力。首先，人可以基于输入的视觉信息感知到运动，包括对运动的觉察、似动现象(Ramachandran & Anstis, 1986)、运动后效(Raymond, 1993)、孔径现象(Wallach, 1935)、整体运动感知(Newsome & Pare, 1988)、基于光流的自身运动感知(Gibson, 1957)等。其次，人能持续地追踪运动的物体(Pylyshyn & Storm, 1988)、预测物体运动轨迹以弥补视觉信息处理的时间延迟(Finke et al., 1986)、预测物体运动以避免碰撞(Lee, 1976)、准确拦截运动的物体(Lacquaniti et al., 1993)等。最后，人还能从感知到的运动中推理潜在结构(Johansson, 1975)、生命性与社会性(Heider & Simmel, 1944; Michotte, 1950)等潜在意义。

构建在感受器水平上的神经环路模型(Barlow & Levick, 1965; Borst & Euler, 2011; Reichardt, 1986)可以解释基本的运动感知，而不少研究则以启发式解释丰富运动体验背后的心理机制。该观点认为，认知系统根据先天的知识或过往经验，将当前信息中的关键线索与相应的运动视觉体验相关联，从而从简单视觉输入的基础上完成运动感知、预测和推理。尽管启发式的观点能解释输入与输出间映射的不对等，但以映射连接的观点看待视觉加工或许未能充分揭示视觉运动加工的全部机制。有学者认为，人类的视觉系统并非是对输入的简单映射，而是基于当前感觉输入和已有的先验知识进行复杂推理的信息加工过程(Bruner, 1973; Marr, 1982)。该推理过程是人类感知觉的核心机制，详细解析该机制是理解人类视觉加工过程的关键。

产生式视觉(generative vision)是近年来视觉领域中最前沿的描述和解释视觉加工推理过程的取向(Tang et al., 2023)，其理论核心是：视觉系统能够推理观测到刺激背后的潜在产生过程，并据此形成视觉体验及开展后续的视觉认知活动。产生式视觉的经典例子是对颜色恒常这一视觉现象的解释。颜色恒常是指物体在不同光照下投射到视网膜的反射光线波长不同时，视觉系统仍能将其知觉为同一种颜色。如图1所示，反射光线不同的区域能够被知觉为相同颜色，而反射光线相同的区域（如A和B）能够被知觉为截然不同的颜色。产生式视觉的观点认为，视觉系统在推理过程中将入射光线的变化纳入考虑，区分了障碍物遮盖和未遮盖区域中入射光线的不同，从而正确推断物体表面特性，产生颜色恒常现象。与启发式理论相比，产生式理论不仅为现象背后的过程提供了清晰的理论和计算描述，也为不同场景中视觉现象的变化和恒定提供了稳定的机制解释(Smith et al., 2023)。

图片包含 图标

描述已自动生成

图1 颜色恒常性作为产生式视觉的典型示例

近年来，产生式视觉的理论取向被逐渐引入视觉运动加工领域，并产生了丰富的成果。视觉场景中的运动对象往往彼此存在联系,视觉系统或能在加工运动信息时感知和利用对象间的关系。不少经典的运动知觉现象体现了视觉系统对运动对象间关系的感知(图 2a) (Duncker, 1929; Johansson, 1973, 1975)，一系列行为和脑神经研究也指出，视觉系统加工运动信息时能够从其结构关系中获得帮助(Brady & Tenenbaum, 2013; Ding et al., 2017; Yantis, 1992)，而破坏运动对象间的结构关系则导致对目标的追踪和记忆绩效大幅下降(Sun et al., 2015; Zhao et al., 2014)。上述证据共同表明，视觉系统以结构化的形式表征运动信息。在此基础上，**申请人及合作者对运动信息视觉层级表征的结构特性和构建过程进行了系统论述，并结合行为实验与计算建模方法对其进行考察(Xu et al., 2017)。**在运动信息的层级表征中，客体运动信息中的共同成分被抽取表征为层级结构的上级节点，各自独特的运动成分则被表征为子节点，客体的真实运动可由根节点至叶节点路径上的所有运动分量叠加而来(图 2b)。该层级结构不仅表达了真实的运动情况，还表达了运动对象间的组织结构。该层级结构还是一个因果结构，由根节点到子节点的路径描述了运动的产生过程，视觉系统通过推理运动背后的产生模式来构建层级表征(图 2c)。研究采用心理物理学实验方法系统论证了对运动信息的视觉层级表征，结果显示对运动对象的预测绩效与层级结构的三个主要特性相符：1）深度，即层级结构越深，运动预测误差越大；2）距离，即预测目标与其他运动对象在层级结构中的距离越远，运动预测误差越大；3）方向，即通过子节点预测根节点，相较通过根节点预测子节点误差更大。此外，研究还构建了贝叶斯层级模型模拟视觉系统构建层级表征的过程，并在运动预测任务中对比层级表征模型、关联模型、人类被试三者绩效在趋势上的异同，进一步为运动信息视觉层级表征提供了证据，并在计算层面初步揭示了视觉层级表征的动态加工机理。

图示

描述已自动生成

图2 运动信息的视觉层级表征及计算模型

上述工作得到了视觉认知领域的重复验证。以此为基础的后续研究工作在知觉(Yang et al., 2021)、追踪(Bill et al., 2020)、记忆(Dasgupta & Gershman, 2021; Galvez-Pol et al., 2020)、社会交互**(Tang et al., 2021; Xu et al., 2018, 2019)**、因果推断(Kawabe, 2019)、事件感知(van der Wal et al., 2018)、视觉-语言关联**(唐宁 et al., 2018)**等诸多认知活动中进一步考察了对运动信息的层级表征及其功能意义，**优化了对视觉运动层级表征的计算模拟**(Bill et al., 2021, 2022; Yang et al., 2021)，并**提出视觉运动加工的“物理-心理”联合推断理论**，认为视觉系统通过同步推断产生运动的潜在物理因素和心理因素，以建构具有解释力和预测力的产生式表征，支撑视觉运动加工顺利开展。这些成果为深入探究层级表征的动态加工机制提供了**理论基础和技术支撑**。

视觉系统顺利推断运动背后的潜在产生过程，依赖于人类心智中已有的关于运动产生规则的先验知识（或称核心知识，core knowledge）。运动的产生过程受对象自身和环境两方面因素约束，其中重力作为环境中最稳定、最常见的因素，其对物体运动的影响尤为重要。近年来不少研究发现视觉系统能够在感知运动(Grealy et al., 2004; Huber & Krist, 2004; Moscatelli & Lacquaniti, 2011)、预测运动(Dessing et al., 2009; Katsumata & Russell, 2012; Zago et al., 2010; Zago & Lacquaniti, 2005)和理解生命性(Nguyen & van Buren, 2023; Szego & Rutherford, 2008)时自动考虑并准确评估重力的影响。此外，无论是通过改变体态(Balestrucci et al., 2021; Zago et al., 2011)、虚拟现实(Cano Porras et al., 2020; La Scaleia et al., 2020)或抛物线飞行(Senot et al., 2012)等方式模拟非标准重力环境，还是只使用视觉线索(Torok et al., 2019)操纵人对重力的表征，受试者均可根据环境和线索定义的重力准确反应。这些结果暗示着，重力或以先验知识的形式存在于人类心智中，且视觉运动加工能够依重力变化产生相应改变以适应环境。

然而，视觉运动加工中重力的具体作用机制，以及视觉运动加工对重力变化的适应机制仍未得到探明。一方面，采用体验模拟或视觉线索方法的研究，本质上并未改变被试所体验到的重力及其对重力的先验知识，而是引入了新的影响因素，使其与原本的重力结合产生新的体验，导致难以区分视觉系统对重力变化的适应是源于先验知识的变化，还是基于线索的补偿机制；另一方面，任务中的行为表现是一系列潜在认知加工的综合产出，对视觉运动加工中重力的作用和适应机制的直接、具象探究，有赖于构建模拟视觉运动产生式加工过程的认知计算模型，使该模型模拟人类在不同重力环境中的视觉加工过程，并与人类表现相比较，以提供全面、直接的证据。根据上述分析，**本项目拟对地表环境、微重力模拟环境和空间环境三类情境中个体的视觉运动加工进行考察，并构建视觉运动加工的计算模型，模拟个体在不同环境中对运动的感知、预测和推理，从而系统探明视觉运动加工中对重力的表征及其动态机制**。

本项目与国内外同类项目存在明显区别：

在思路上，本项目**首次提出“物理-心理”联合推断理论**，阐明物理因素对视觉运动加工的具体影响机制，为生物运动-非生物运动的认知加工提供**统一框架**。在方法上，本项目借助微重力环境实现对重力的彻底剥离，并重点关注从重力环境变换到微重力环境，以及从微重力环境变换到重力环境的**长时程过程中，视觉系统的适应与再适应过程**，从而直接揭示视觉运动加工过程中重力的作用及对重力的适应，在**思路和方法上具有明显的创新性**。

同时，本项目从感知和预测两个方面对视觉运动加工进行系统探讨，并基于领域内最前沿的“物理-心理”联合推断理论，通过认知建模方法对重力的影响进行量化和动态模拟，从而直接考察视觉运动加工中对重力的表征及其动态变化机制。该方法以小样本建模为特点，适用于航天领域这一特殊研究场景，强调所建模型的可解释性、可迁移性和个性化，属目前领域内最前沿的建模方法之一，在**理论和技术上具有明显的先进性**。

三、科学与应用目标

本项目聚焦于视觉运动加工机制这一领域内热点问题，以“物理-心理”联合推断理论为基础，以重力为切入点，探明视觉运动加工中环境的作用机制和适应机制，从而完善视觉运动加工的产生式理论，为变化环境中个体对运动的推理和适应提供解释和预测。针对上述科学问题，本项目形成以下关键科学目标和应用目标：

1. 探明重力在视觉运动加工中的具体作用机制，并构建计算模型，模拟不同重力环境下个体对运动信息的感知和预测，据此明晰视觉运动加工过程中对重力的表征。
2. 探明视觉运动加工对重力变化的适应机制，包括视觉运动加工如何随重力变化、其适应时间及临界水平，并构建计算模型，模拟视觉运动加工对重力变化的动态适应过程。
3. 揭示重力变化环境下视觉运动加工中可能的个体差异，凝练关键因素和指标，构建可用于测量和区分的工具，为人才选拔和训练提供支持。

四、

**实验三 生物运动预测**



图6 （a）实验四运动模式示意图；（b）实验四任务流程图

实验参数。实验程序用python语言编写，并打包为可执行exe文件。在Surface Pro电脑上运行，被试以触屏方式反应。背景为空旷、无重力线索的室内环境。青蛙和虫子用不同颜色的圆形表示（0.4°×0.4°），青蛙的初始位置在背景中下侧墙面上，虫子位于空中随机位置。蛙吃虫运动轨迹构建方式如下（图6a）：青蛙跳跃的初始运动速度v=3°/s，与x轴夹角取值范围（0°、15°、45°），青蛙受到竖直向下的重力加速度ag=9.8°/s2，青蛙捕食的目标虫子做逃离青蛙的运动，v=3°/s，另外2个干扰子做随机运动，v=3°/s。

实验流程。每个试次开始后，播放蛙吃虫运动轨迹，1s后青蛙消失，间隔0.8s~1.5s时间后屏幕上显示“？”，被试需要在触屏上点击的方式报告消失的青蛙此时所在位置（图6b）。青蛙的三种初始角度各30个试次，总共90个试次，每个试次大约5s，预计单次实验总耗时约8min。

结果预期**。**被试点击位置与消失青蛙实际位置之间的差值为预测偏差。比较不同实验阶段的预测偏差，对于初始运动方向15°和45°，预测偏差更接近与地面重力一致的真实运动轨迹。

**计算建模**

图形用户界面

描述已自动生成“物理-心理”联合推断模型假设了物体运动的产生过程（图7）：1）最上层为重力/微重力因素，对环境中所有对象作用相同；2）中间层包含两方面，对于所有运动对象均考虑其可能受到的其他外力（如：发射的初始加速度），对于生物运动还考虑生命体的心理状态带来的内驱力（如：追逐），内驱力的产生规则遵循生命体意图原则（如：目标导向的理性原则）；3）最下层综合考虑所有驱动力，根据运动公式合成可被感知的运动。产生式模型的各部分均为概率形式，根据观测到的运动可逆向推理产生过程。推理过程遵循贝叶斯定理，具体通过蒙特卡洛采样或适用的高维数据采样逼近方法实现。

图7 “物理-心理”联合推断模型原型示例及各部分建模思路

以上述模型作为原型，针对三个实验任务进行认知建模，比较引入真实重力和微重力的模型，在不同阶段对被试的模拟效果（以BIC作为衡量模型的指标）。

**4.2**

五、创新性与预期成果

1. 预期产出重力变化对视觉运动加工过程的影响机制及其适应机制的理论模型，为重力变化环境下设计符合人类视觉特性的信息呈现和操作设备提供理论指导；
2. 预期产出模拟人类视觉系统适应重力环境变化的理论模型和计算模型，能够区分个体在适应性方面的差异，为人才选拔和培养提供理论和技术支持；
3. 预期形成研究报告，并发表至少2篇高水平学术论文，拟冲击国际顶级学术期刊及其子刊。

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