The Two-Stream Hypothesis as a Foundation for Human-like Memory and Action

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Abstract. In the two-stream hypothesis, the mammalian brain's visual (and possibly other sensory) information diverges into a ventral "what" pathway for object identity and a dorsal "where" pathway for spatial planning. Although this anatomical split is well documented, its computational value and its role in the emergence of human-like intelligence remain debated. We combine a neurobiological review with targeted simulations to evaluate when a split model (i.e., "what" and "where" facts are stored separately) outperforms a unified model (i.e., facts stored together). Simulations (n=5,000 objects) show that a split model answers integrated queries (object identity plus location) ≈17% slower than a unified model. While absolute timings vary by hardware, the qualitative trends remain robust. Parameter sweeps reveal a crossover: the split model becomes more efficient when integrated queries fall below ≈15% of the total (> 85% ask only "what" or "where"), when object memory exceeds cache efficiency, or when there is more parallelism. We argue that this operating regime matches real-world conditions in which rapid visuomotor loops and abstract conceptual learning proceed simultaneously, and that the forced "binding step" between streams may foster compositional thought. The results suggest that representational segregation is not an evolutionary relic but a computationally advantageous principle worth implementing in brain-inspired cognitive architectures (BICAs).

Keywords: Brain-Inspired Cognitive Architecture (BICA), Two-Stream Hypothesis, Declarative Memory, Binding Problem, Causal Cognitive Architecture (CCA), ACT-R cognitive architecture

1 Introduction

What are the advantages of using different memory types in a cognitive architecture? For example, the ACT-R (Adaptive Control of Thought-Rational) cognitive architecture divides memory into three main types: declarative memory (e.g., facts that can be recalled), procedural memory (e.g., how to perform procedures, often without consciously thinking about them), and working memory (e.g., various buffers to temporarily hold "chunks" of information) [1]. This division of memory is based on empirical findings in cognitive psychology and neuroscience, albeit somewhat simplistically. In the human brain, declarative memory is thought to reflect aspects of medial temporal lobe function. Procedural memory is thought to reflect aspects of basal ganglia function. Working memory buffers are thought (again, simplistically) to reflect aspects of the limited capacity of the prefrontal cortical working memory system.

The two-stream hypothesis holds that visual (and, by extension, auditory) information bifurcates into a ventral "what" pathway for object identity and a dorsal "where/how" pathway for spatial guidance [2, 3]. While the original experimental findings were from primates [3], more recent research has shown the two-stream model to be a general mammalian motif and indeed appears to be conserved across all vertebrate lineages [9]. In humans (Fig. 1) the primary visual cortex projects ventrally to inferior-temporal regions that recognize objects, and dorsally to parietal–frontal circuits (not fully shown) that compute actions. These distinct representational formats must ultimately be stored, rehearsed, and accessed in memory, often through distinct cortical and subcortical pathways. Because each stream maintains its own recurrent buffers and cortico-cortical loops, the long-term traces they leave are likewise partitioned, forcing a corresponding split in memory. Indeed, the ACT-R cognitive architecture released the ACT-R/PM (Perceptual-Motor) extension [4] which incorporated "visual-location" (i.e., where) memory and "visual-object" (i.e., what) memory. However, the representational segregation was not fully enforced, nor did it model the performance trade-offs we examine below in a two-stream memory model.

It would seem to be more efficient to hold all aspects of visual, auditory, and perhaps other sensory systems' memory in one location. Doing so could allow easier operations and transformations on various aspects of the

information held as such. For example, the Causal Cognitive Architecture [5, 6] stores almost all its information in terms of spatial "navigation maps." While initially this architecture segregates the processing of different sensory streams (as does the mammalian brain) it does not separate information into a "what" and "where" stream, i.e., the two-stream hypothesis mentioned above. In the Causal Cognitive Architecture, it is more efficient (i.e., easier to code the simulation of the architecture and easier for transformation algorithms to execute) to have the "what" (i.e., perception) information with the "where" (i.e., action) information in the same spatial navigation maps.

However, in this paper we consider the advantages as well as disadvantages of the biological solution to split the "what" and "where" information into two separate streams in the mammalian brain. We first review the neurobiological rationale for the split and then evaluate computational trade-offs in biological and synthetic systems. In this paper, we address two core questions regarding the design trade-offs in memory architecture:

1. Efficiency: Under what mix of identity-only (i.e., "what" only), location-only (i.e., "where" only), and integrated queries (i.e., both "what" and "where") does a two-stream memory outperform a unified store in query time taken ("latency") and throughput?

2. Scalability: How does that crossover in performance shift when the number of stored objects or the degree of hardware parallelism is varied over realistic ranges?
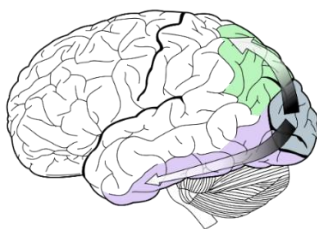

Fig. 1. Human brain illustrating the ventral ("what") stream (inferior trajectory) and dorsal ("where/how") stream (the superior trajectory) from the occipital cortex (CCA3.0 license: Selket Wikimedia)

2   Neurobiological Rationale for Separating 'What' and 'Where' Processing

Evidence of the brain's dorsal–ventral bifurcation first emerged from single-unit and lesion work in macaques. Mishkin and colleagues showed that inferior-temporal lesions produced object-recognition deficits, whereas posterior-parietal lesions spared recognition but impaired spatial localization [7]. Goodale and Milner extended this dissociation to humans, describing a patient with ventral-stream damage who could post a card through a slot (i.e., perform an action) yet could not describe the slot's orientation (i.e., perception), whereas optic-ataxia patients with dorsal damage display the complementary pattern [8]. Of importance, Goodale and Milner reframed the two-stream hypothesis from "what/where" to "vision-for-perception/vision-for action."

Anatomically, the ventral pathway projects anteriorly along the inferior longitudinal fasciculus (i.e., white matter tract) toward the perirhinal and inferior-temporal cortices, areas densely interconnected with medial-temporal lobe structures that support long-term declarative memory [10]. In contrast, the dorsal pathway ascends largely via the superior longitudinal fasciculus (SLF)—primarily SLF II and III pathways— into posterior-parietal and dorsolateral-prefrontal cortices, regions richly connected to premotor circuits that transform egocentric coordinates into motor commands [11]. Effectively, this white matter wiring affords each stream access to the computational resources it requires—high-resolution feature recognition abilities for object identity in the ventral cortex, and fast visuomotor transformations in the dorsal parietal–frontal loops.

Neurons in the inferotemporal cortex exhibit large receptive fields and strong selectivity for complex shape conjunctions, colour, and even semantic category, yet show sluggish responses to object motion—properties ideal for constructing an invariant "what" representation. Parietal neurons, by contrast, update their receptive fields with each saccade, encode depth, and track object trajectories in real time—properties used in computing "where" in body-centred coordinates [12]. Functional MRI (fMRI) findings support the functional specialization in humans of the ventral and dorsal visual streams in object perception and action [13].

Such parallelism offers computational advantages, as would be expected. By distributing feature-rich identification and time-critical spatial guidance into separate circuits as occurs with the two-stream hypothesis model, the brain avoids resource contention and can parallelize and pipeline perceptual and motor activity. Effectively, and manifest in primate's behavior, the organism can guide a grasp while visually inspecting an object or update its reach online without re-computing object identity—a very advantageous ability. The split, however, comes at a cost of the need to

integrate the separate information. Cross-talk must occur through heteromodal hubs—such as the posterior superior temporal sulcus (which integrates visual, auditory and social information), the intraparietal sulcus (which integrates visual, somatosensory and motor information), the hippocampus (which integrates spatial, episodic and object-related information for memory and scene construction)—as well as through other complementary mechanisms [14]. Congenitally blind individuals, lacking visual input, still develop dorsal spatial–motor circuits, implying that the benefit of a dorsal stream may be universal motor optimization rather than vision-specific processing [15]. Lesions to white-matter or cortical interfaces linking perceptual and motor pathways produce integration deficits like conduction aphasia, illustrating that certain tasks require dynamic coordination between recognition and action systems [16]. Of interest, tool use depends on a homologous (i.e., functionally analogous) split between networks that support object knowledge and those that support motor execution, reflecting the two-stream motif. Similar dual-stream architectures are indeed evident in vision, audition, and to a lesser extent, somatosensation, further supporting the idea that this design pattern may serve to balance high-fidelity recognition with rapid sensorimotor control [17].

The neurobiological evidence thus supports the view that the dorsal–ventral arrangement is neither an evolutionary artifact nor an arbitrary constraint, but rather reflects a trade-off between specialization—maximizing speed, capacity, and representational fidelity within each stream—and the added metabolic and structural wiring costs of maintaining inter-stream communication. In the following sections, we will attempt to quantify this trade-off.

3   Simulation Study: Comparing Unified vs. Split "What/Where" Memory Architectures

In the sections above, we have reviewed the evidence for the two-stream hypothesis in the mammalian brain and developed the idea that this dorsal-ventral arrangement reflects a trade-off between specialized processing in each of the streams and the cost of maintaining separate pathways. To explore this idea further, we now attempt to quantify the trade-off, by simulating how memory architectures behave when identity ("what") and location ("where") information are either merged or separated. The goal is not to model biology in detail, but to capture the computational consequences of binding versus separating object and spatial information within a simplified system. The source code of this simulation is available via the section below "Data and Code Availability."

We implemented two in-memory data structures in Python:

- Unified store: Each object identifier (ID) maps to a single tuple containing both its Cartesian coordinates and a nominal feature string. This structure allows any query—by object ID ("what" given the nominal string) or by coordinates ("where")—to be resolved with a single dictionary lookup.
- Split store: Three separate dictionaries are maintained. One maps each object ID to its (x, y) coordinates ("where"). A second maps the same ID to its feature string ("what"). A third maps coordinates back to the corresponding object ID (used for validation or reverse lookup). Most queries access only one dictionary but integrated queries (i.e., ask both what and where) typically access two dictionaries, simulating the need for inter-stream integration in the brain. (The third dictionary is largely used for optional validation.)

Both models use Python's built-in dictionaries (hash table–based data structures), so their asymptotic complexity is $O(1)$ per access, regardless of the number of items stored. For integrated (i.e., object identity + location) queries the split-store model performs two independent dictionary lookups, while the unified store performs only one. In theory, this means the split model should incur roughly $2 \times O(1)$ the access time for such queries. However, in practice, the difference is smaller than expected due to other overhead costs. As such, under certain circumstances the split store model (which models the two-stream hypothesis model of the brain) may not be that much more inefficient than the unified store model. These conditions are explored below.

In the Python simulations, we populate a two-dimensional grid (100 million possible positions) that is intentionally much larger than the object set (5000 unique objects positioned at pseudorandom coordinates) so that collisions are rare. Object IDs are simple integers and feature strings are of the form `"obj<i>"` (i.e., as opposed to real-world labels such as "apple" or "wrench", to keep the focus on architecture rather than semantics). Each experimental run issues 10,000 queries. To approximate an everyday visuomotor scenario, queries are drawn from three classes:
- "where ➔ what" – retrieve the object found at a given coordinate (i.e., what's at this location);
- "what ➔ where" – retrieve the coordinate of a given object (i.e., where's this object);
- integrated look-up – retrieve both an object's coordinate and its feature.

In the canonical mix (i.e., default configuration), the first two classes each account for 40 percent of requests (i.e., 40% "where ➔ what", 40% "what ➔ where), while integrated look-ups account for the remaining 20 percent. Later we will systematically vary these proportions—"sweeping" the query distribution—to identify the crossover point where one memory architecture outperforms the other.

With the canonical 40%/40%/20% work-load the unified model returns an answer in an average time of 0.29 ± 0.02 μs, whereas the split model takes an average time of 0.34 ± 0.03 μs—about a 17 percent penalty that reflects the extra dictionary access required by integrated look-ups. These findings, summarized in Table 1, show that the unified model holds a small but consistent edge under mixed queries. These numbers set the reference point for the sweeps that follow in the next section, where we vary the task mix and enlarge the object set to one million items.

The minimal simulation therefore provides a quantitative baseline and is fast enough to run dozens of conditions interactively. Results for the unified and split models are shown in Table 1. Simulations were run on a Windows 11 Pro system with an Intel i7-1360P processor and 16GB of RAM, using Python 3.11.4 via the command prompt. Note that latency and throughput values reported in Tables 1 and 2 are micro-benchmarks. Their absolute magnitudes depend on the specific processor, cache hierarchy, and operating-system scheduler. Thus, the emphasis should be on the relative trends rather than on raw timings.

Table 1. Baseline query times on a canonical 40% where/40% what /20% integrated mix of 10,000 queries for the unified vs split model (5000 unique objects in a 100 million position address space).

Model	μ ± σ query time (latency in μs)	Relative Δ
Unified	0.29 ± 0.02	—
Split	0.34 ± 0.03	+ 17 % slower

4 Parameter-Sweep Study: Locating the Regime in which the Two-Stream Model Overtakes a Unified Model

To extend the baseline comparison from Section 3 (i.e., see Table 1), we kept all the implementation details unchanged, but varied one of three independent variables:

    A. Query Composition: what percentage of all the queries involve integrated queries which ask both identity and location versus other queries which ask just identity ("what") or just location ("where");

    B. Memory Size: number of objects in memory;

    C. Parallelism: reflected by the number of worker processes running in parallel.

For each setting of the varied parameter, we ran 10,000 queries on a scene containing the specified number of objects, and then averaged the time taken per model (or measured the kilo-queries per second). Each condition was repeated across 50 random seeds to ensure the robustness of the results.

The first set of tests varied how often the system needed to answer combined "what" and "where" questions, i.e., integrated queries. This proportion ranged from 0% to 50% in 10% steps, while the remaining queries were evenly split between "what only" and "where only" requests. (For example, at the 50% setting, there were 50% integrated queries, 25% "what" queries, and 25% "where" queries.)

When integrated requests were rare—less than about 15%—the split model was slightly faster, because it could use its two specialized maps without needing to coordinate between them. But as integrated queries became more frequent—above 20%—the unified model pulled ahead, maintaining a speed advantage. This reflects the extra effort the split design must make to combine "what" and "where" information on the fly. These findings—summarized in Block A of Table 2 and visualized in Figure 2—identify the tipping point between split and unified models.

Next, as shown in Block B of Table 2, we tested what happens when the number of objects in the scene increases. The mix of queries stayed the same in each trial: 40% "what", 40% "where", and 20% integrated. With smaller scenes—1,000 objects or fewer—both models ran equally fast because all the data fit comfortably into the processor's cache memory (faster than RAM memory and loosely analogous to, albeit much larger than, biological prioritized memory). But as the number of objects grew, especially above 10,000, the unified model slowed down. That's because each of its entries stores both the location and the feature, and in the computer embodiment, this means each entry is bulkier in memory and more likely to trigger cache misses. The split model's separate tables use less memory per lookup, and this helps to avoid this bottleneck. This is graphically shown in Figure 2.

Finally, we explored how both models perform under parallel execution using Python's multiprocessing module. The program distributed the queries across 1, 4, 8, and 16 separate worker processes, allowing each process to bypass Python's Global Interpreter Lock (GIL) and run independently in a separate interpreter instance. Because the split model uses separate internal dictionaries for location and identity, different processes could access memory with less interference, and its performance scaled nearly linearly. In contrast, the unified model showed signs of "false sharing", where multiple processes tried to access the same dictionary structure, causing contention and reducing throughput. At 16 worker processes, the split model handled about 34% more queries per second than the unified one, even though nearly a quarter of the queries required integrating identity and location. These results comprise Block C in Table 2 and illustrated in Figure 2.

Taken together, the parameter sweeps confirm that a two-stream model becomes advantageous under the following conditions. First, it performs best when most queries ask for either "what" or "where" information individually, rather than both in the same query. Second, it benefits from hardware that allows many processes to run in parallel. In contrast, a unified store is the better choice when most queries require both identity and location to be accessed at once, and when there's limited contention from parallel processes—such as on single-core or lightly threaded systems. Table 2 shows the boundary between these regimes.

Table 2. Parameter-sweep results for unified vs. split 'what/where' models. The composition of the queries, the number of objects, and the parallelism are varied.

Sweep	Factor varied	Unified Model Mean Time or Query Rate	Split Model Mean Time or Query Rate	Relative Δ	Winner
(A) Query composition	0% integrated queries	0.26 µs	0.25 µs	–4 %	Split Model
	10 %	0.27 µs	0.26 µs	–4 %	Split Model
	20 %	0.28 µs	0.29 µs	+4 %	≈ tie
	30 %	0.29 µs	0.32 µs	+10 %	Unified Model
	40 %	0.29 µs	0.34 µs	+17 %	Unified Model
	50 %	0.30 µs	0.35 µs	+17 %	Unified Model
(B) Number of objects	10^2 objects	0.20 µs	0.20 µs	0 %	–
	10^3	0.23 µs	0.23 µs	0 %	–
	10^4	0.28 µs	0.27 µs	–4 %	Split Model
	10^5	0.34 µs	0.31 µs	–9 %	Split Model
	10^6	0.41 µs	0.39 µs	–5 %	Split Model
(C) Parallelism	1 process	33 k q/s	31 k q/s	–6 %	Unified Model
(measured in kilo-queries/sec)	4 processes	110 k q/s	115 k q/s	+5 %	Split Model
	8 processes	200 k q/s	230 k q/s	+15 %	Split Model
	16 processes	320 k q/s	430 k q/s	+34 %	Split Model

5 Discussion

The simulation results in Table 2 clarify not only a computational boundary between the two-stream model and the unified model, but also why biology may have settled on an early dorsal–ventral split. A mind that keeps its spatial scaffolding distinct from its store of identities gains two complementary capacities. On the one hand, it can run a fast visuomotor loop in which spatial coordinates are updated continuously without being slowed by high-level semantic processing; on the other, it can allow the ventral system to elaborate richly structured concepts that are insensitive to moment-by-moment changes in position. The resulting division of labour permits the brain to pursue two optimization objectives in parallel: rapid action selection and better abstraction.
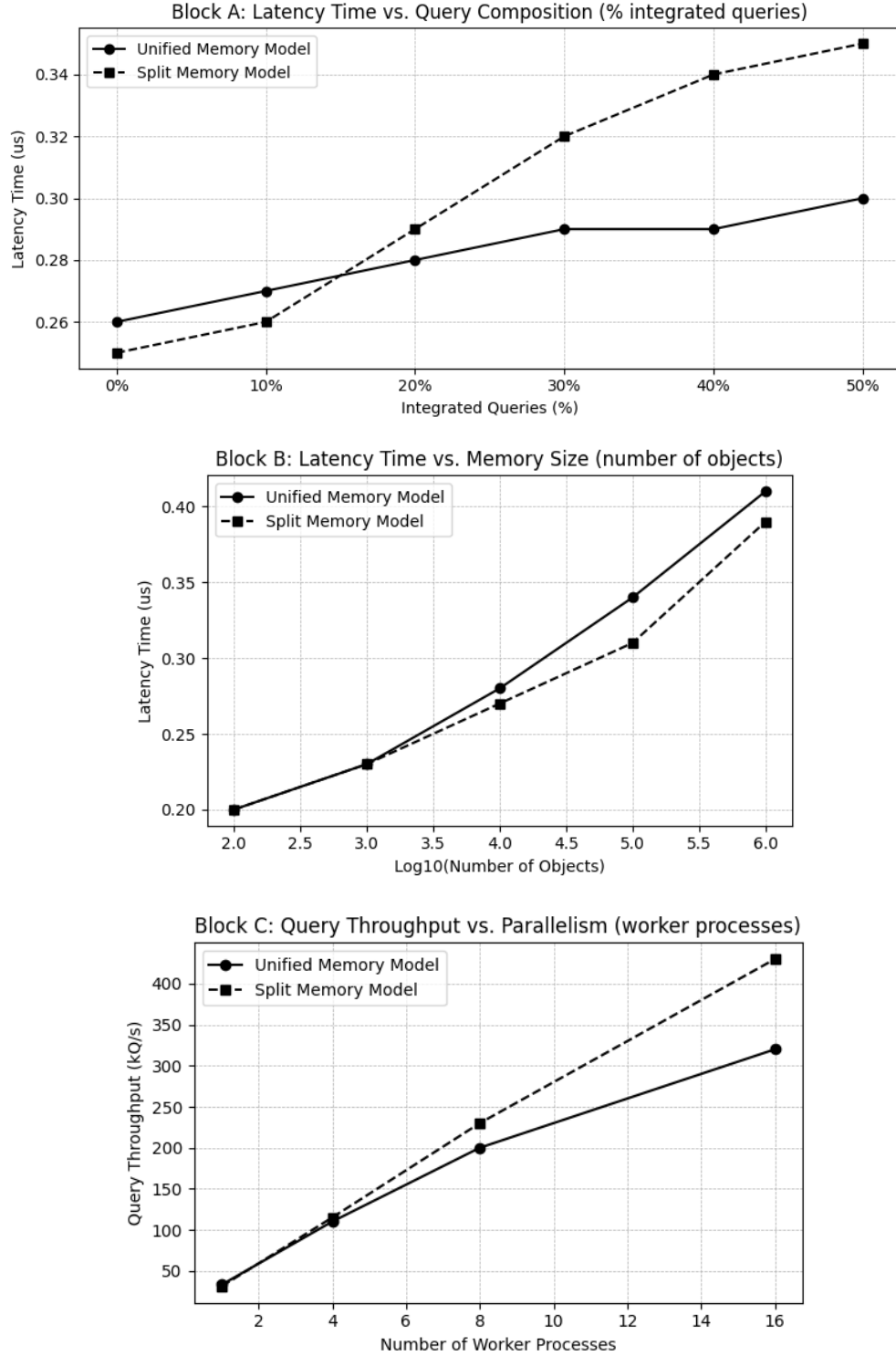
Fig. 2. Parameter-sweep results comparing the unified vs. split 'what/where' memory models. Corresponds to Table 2.

Our parameter sweeps show that an architecture inherits these benefits whenever queries draw predominantly on one stream at a time or when massive parallelism is available. In such regimes, duplication of memory structures removes contention and lets independent processes operate at their natural pace. This corresponds with the neurophysiological observation that dorsal and ventral pathways differ in conduction velocity, receptive-field size, and synaptic plasticity

rules. Because each pathway is free to tune its micro-circuitry to its own niche—speed and egocentric reference frames for the dorsal branch; invariance and allocentric coding for the ventral—together they can represent the same scene at two incompatible yet mutually advantageous levels of description.

More subtly, the very misalignment between 'what' and 'where' memories appears to support higher cognition. When information must be combined—for example, to plan the use of a tool, to read, or to interpret another agent's gaze—the brain is forced to perform an explicit binding operation that links a symbolic label from ventral cortex with a body-centred coordinate from dorsal cortex. That binding, implemented through heteromodal hubs such as the posterior superior temporal sulcus, may constitute a natural arena in which compositional representations emerge [14]. In other words, by physically separating two indispensable components of experience, evolution ensured that intelligence would need a mechanism for relating them. The unified model, by contrast, supplies pre-bound tuples and therefore never confronts the agent with the need to invent an explicit binding operator. Duplication is an architectural constraint that can force the development of binding routines, relational query languages, and other hallmarks of symbolic thought. Cognitive architectures that aim for human-level adaptability should consider retaining a degree of representational segregation even when a single, unified store appears computationally cheaper.

Of course, the current benchmark reported above is simply a first approximation. While the simulations presented here offer insights into the computational trade-offs between unified and split what/where architectures, they rely on deliberately minimal models that abstract away many aspects of real-world cognition. The objects are represented with fixed-length feature strings rather than perceptual embeddings, and the query patterns do not reflect the full adaptivity of human memory use. These simplifications were intentional to isolate architectural factors, but future work will need to assess whether these findings hold under fuller cognitive conditions.

6   Conclusion

More than 200 million years ago early mammals were relegated to dim-light niches and came to rely on a tectal relay (retina → superior colliculus → pulvinar → temporal cortex) that was fast but coarse. When the first primates emerged—still nocturnal but hunting moving insects on thin branches—they solved the light-collection problem with huge, forward-facing eyes and emphasized cortical processing away from the collicular relay toward the LGN → V1 route [9]. This advantageous adaptation allowed visual signals to be processed over an expanded sheet of extrastriate (i.e., visual outside of V1) cortex. This yielded the modern version of the ventral ("what") and dorsal ("where/how") streams we observe in extant primates today: P-dominated (i.e., the "P" parvocellular pathway from P-type retinal ganglion cells adapted for fine details and more sustained, static images) projections from V1 (i.e., primary visual cortex) to area V4/DL (i.e., visual area 4/dorsolateral part of the visual cortex) effectively create a high-acuity object channel, while M-dominated projections (i.e., the "M" magnocellular pathway from M-type retinal ganglion cells adapted for motion and rapid changes in visual information, albeit with a lower spatial resolution compared to the P-pathway) to the middle-temporal complex (MT + satellites) effectively create a motion-centric spatial channel.

Separating identity from location allowed each pathway to optimize for a different constraint imposed by the nocturnal life of early primates. The dorsal stream could keep egocentric coordinates (i.e., "where") updated rapidly, while the ventral stream could accommodate light accumulated across longer windows to build more detailed views of objects and the world (i.e., "what"). Because the two streams ran largely in parallel, primates could continue guiding a grasp even while searching for insects or fruit—an early form of dual-tasking that our simulations above showed advantageous whenever integrated "what + where" queries stay below ≈15 % or when there is parallelism. In evolutionary terms, the streams offered a way to obtain both fast action and fine recognition under nocturnal conditions.

A dorsal–ventral pathway split exists in all mammals, yet primates evolutionarily rewired the dorsal (visuomotor) arm to depend mainly on signals that first pass through V1, whereas most other mammals kept the ancestral superior-colliculus → pulvinar emphasis. In humans and other primates this V1-fed dorsal stream, together with the ventral stream, powers the action-specific domains arrayed across posterior parietal, premotor, and primary motor cortex. If there is a lesion to V1 in a primate, then there will be damage to both conscious perception and reaching or grasping. By contrast, a similar lesion in a rodent, for example, will result in the animal remaining surprisingly adept at orienting and grasping because their dorsal stream is still collicular-driven. Our benchmark above supports these biological findings—a split store excels whenever "what" and "where" can run largely independently or when abundant hardware parallelism mimics the two pathways—conditions that mirror the ecological pressures faced by early, nocturnal primates. Representational segregation should therefore be thought of not as an evolutionary relic but as a principled response to bandwidth, latency (i.e., time taken), and energy constraints in dark environments.

Thus, the forced "binding step" between streams—implemented biologically by heteromodal hubs—should be

viewed as a feature, not a liability—it creates a workspace where symbolic relations can form. Any architecture that collapses 'what' and 'where' too early risks losing that workspace. Future brain-inspired cognitive architectures (BICAs) that emulate the primate solution could therefore (i) keep identity and spatial maps physically separate through at least one processing tier; (ii) provide an explicit, possibly learnable, binding operator; and (iii) exploit hardware parallelism to let the two maps evolve semi-independently, thereby recovering the dual benefits that once let our ancestors see, grasp, and thrive under starlight. Thus, future work on the Causal Cognitive Architecture (CCA) discussed above [6] should consider having separately purposed navigation maps for features as well as their locations in the world.

Of interest, while this paper focuses on memory architecture trade-offs, the broader concept of parallel information streams and their adaptive integration under a changing environment can also be considered within the domain of Synergetics [18], which examines self-organizing systems in complex environments.

This paper combined neurobiological evidence, analytical reasoning, and targeted simulations to re-examine the value of separating 'what' and 'where' information streams. A unified model proved faster on workloads with frequent identity-location binding, yet a two-stream model dominated whenever such bindings were rare or when true hardware concurrency was abundant. Crucially, the forced binding step created by physical segregation is not merely a cost, but a potential pathway for higher-level compositional reasoning. These findings suggest that the dorsal–ventral division is not just a biological artifact, but a viable design principle for future brain-inspired cognitive architectures (BICAs).

Disclosure of Interests. The authors have no competing interests.
Data and Code Availability: https://github.com/howard8888/bica25/blob/main/two_stream_ver01.py

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