

FORSCH-PROV0438 biointelligenz-technik v1.0 (EN)

- [Bio-Intelligence as Engineering](#)
 - [Preliminary note on the position of this work](#)
 - [1 A three-level distinction](#)
 - [2 Substrate taxonomy](#)
 - [3 State of the art](#)
 - [4 Bottlenecks](#)
 - [5 Audit of common claims](#)
 - [6 p/6 analysis \(instance of FORSCH-0083\)](#)
 - [7 Guardrails for this strand](#)
 - [8 Novel approaches](#)
 - [9 Connections](#)
 - [10 Experimental programme](#)
 - [11 Open questions](#)
 - [12 Sources](#)
 - [13 Glossary](#)

Bio-Intelligence as Engineering

Substrates, interfaces, experiments — a transdisciplinary landscape survey with an experimental programme

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Preliminary note on the position of this work

Three axes are already occupied in this strand:

Axis	Work	Question
Substrate and experience	FORSCH-0364	What does experience depend on, if not carbon?
Organisation	FORSCH ≥0393 (kognition-ohne-zentrum)	Does cognition require a centre?
Engineering feasibility	this work	What can actually be built from which substrate under which conditions — and how much of it is open to non-institutional research?

This work reopens neither the consciousness question nor the organisation question. It treats both as boundary conditions and asks the engineering question: parameters, bottlenecks, cost, legal status, access — and from these an experimental programme that can be started with existing workshop infrastructure.

Evidence status. Every factual claim carries a marker: [P] peer-reviewed or primary source verified by DOI, [S] secondary source or vendor statement, [O] open, a claim only, not independently replicated. Vendor statements on energy efficiency and performance are [S] or [O] throughout, because the vendors are also stakeholders.

Exclusions. Military, weapons and defence applications are excluded across all strands. In this field that is not a formal clause: several of the referenced works on cyborg insects and biohybrid sensing are funded through naval research grants. The exclusion therefore bites substantively and is applied to specific approaches in section 7.

Availability. This work runs on the platform. Tools, worked experimental documentation, build documentation and teaching modules live at syntagma-science.com, where they are maintained, versioned and developed further. The text itself — landscape survey, bottleneck analysis, ρ/δ analysis, guardrails, open questions and all evidence — stays free under CC BY 4.0, fully citable, and is deposited as a reference edition pointing to the platform.

Since 2026-10-06 the order is reversed: not an archive holding with an offer attached, but a platform with the finding deposited freely alongside. Nothing about what is open changes — the finding stands complete in the free part and stays there.

1 A three-level distinction

The umbrella term “bionics” covers three technically unconnected approaches. Conflating them is the most common source of misplanning in this field.

Level	Definition	Living matter in the final product	Example	Maturity
B1 structure transfer (bionics proper)	A biological form, structure or process principle is abstracted and realised in non-living material	no	Exponential horn after cricket stridulation; topology optimisation after bone trabeculae	production-ready
B2 biohybridics	Living tissue is built into a technical system as actuator, sensor or controller	yes, as a component	Muscle-driven soft robotics; insect antenna as gas detector	lab to demonstrator
B3 substrate computing	The computation itself takes place in the biological medium	yes, as the computing element	Brain organoid on MEA; fungal memristor; DNA strand displacement	early to niche

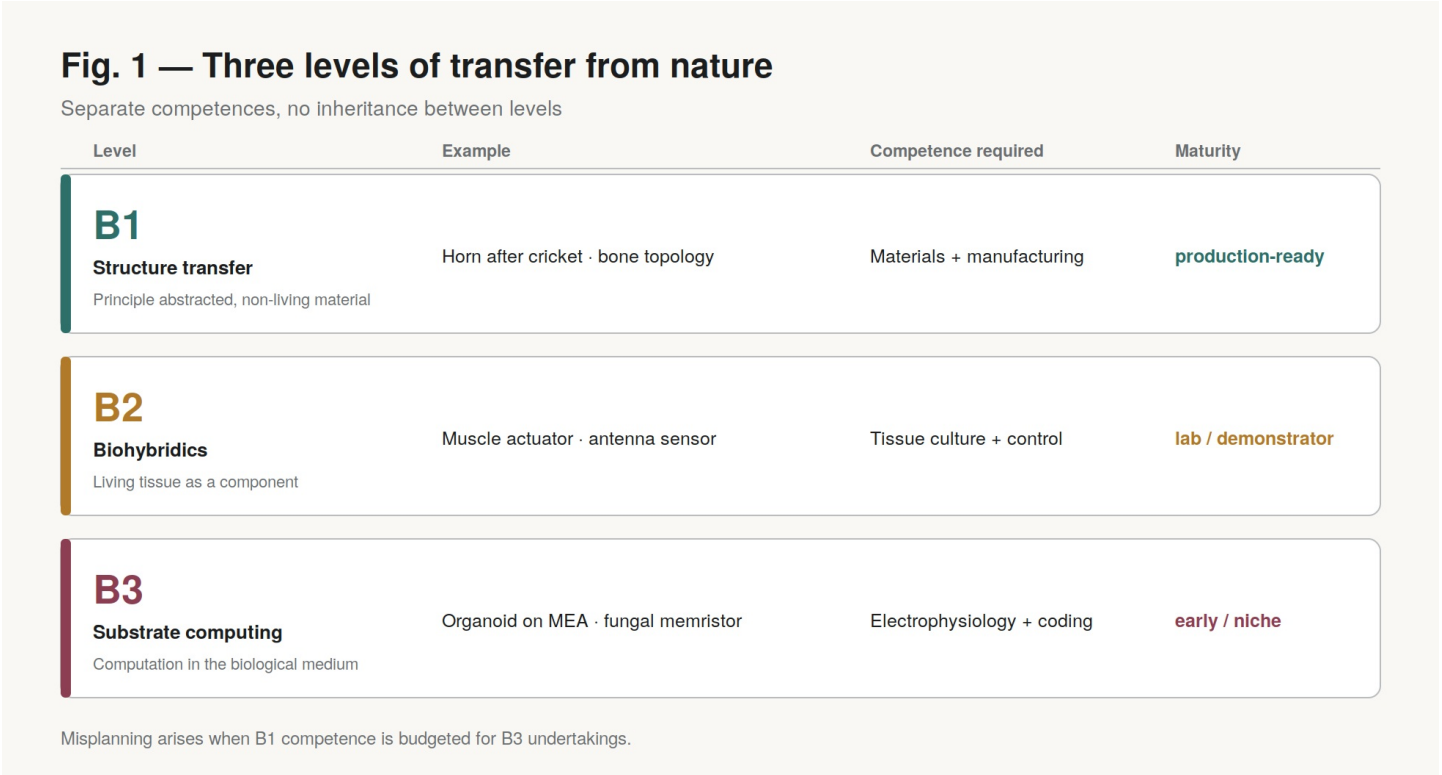


Fig. 1 — Three levels of transfer from nature. Separate competences, no inheritance between levels.

The levels do not inherit from each other. B1 demands materials and manufacturing competence, B2 tissue culture plus

control engineering, B3 electrophysiology plus coding theory. Mastery of B1 yields nothing for B3 except manufacturing capacity for peripherals — which, per section 9, is the real point of connection.

2 Substrate taxonomy

Six substrate classes with the parameters that decide feasibility. Cost figures are orders of magnitude for a single build, not quotations.

Substrate	Information carrier	Timescale	Energy per operation	Maturity	Access for individual researchers	Legal status (AT)	Animal-free achievable
Human brain organoids (hiPSC)	spikes, synaptic plasticity	ms-h	biological, see §5	cutting-edge	remote platform or collaboration	BSL-2, ethics approval	conditionally, see §8 N1
Primary / immortalised neuronal cultures	spikes	ms-h	biological	established	lab collaboration	BSL-2; animal-research law for primary culture	no, for primary culture
Fungal mycelium (live / dehydrated)	electrical spikes; memristance	ms-s / µs-ms	not cleanly measured	early	fully open	no restriction	yes
Slime mould (<i>Physarum</i>)	protoplasmic streaming, network topology	s-h	not measured	early	fully open	no restriction	yes
DNA / nucleic acids	sequence, hybridisation cascade, folding	s-h (computing), centuries (storage)	chemical	storage mature, computing niche	oligo ordering possible	no restriction for synthetic oligos	yes
Organic semiconductors (OECT / memristor)	ionic / electronic conduction	µs-ms	see §5	lab to pre-production	open, printable	no restriction	yes

Fig. 2 — Substrate map

Maturity against access barrier · circle colour = ethical precautionary load

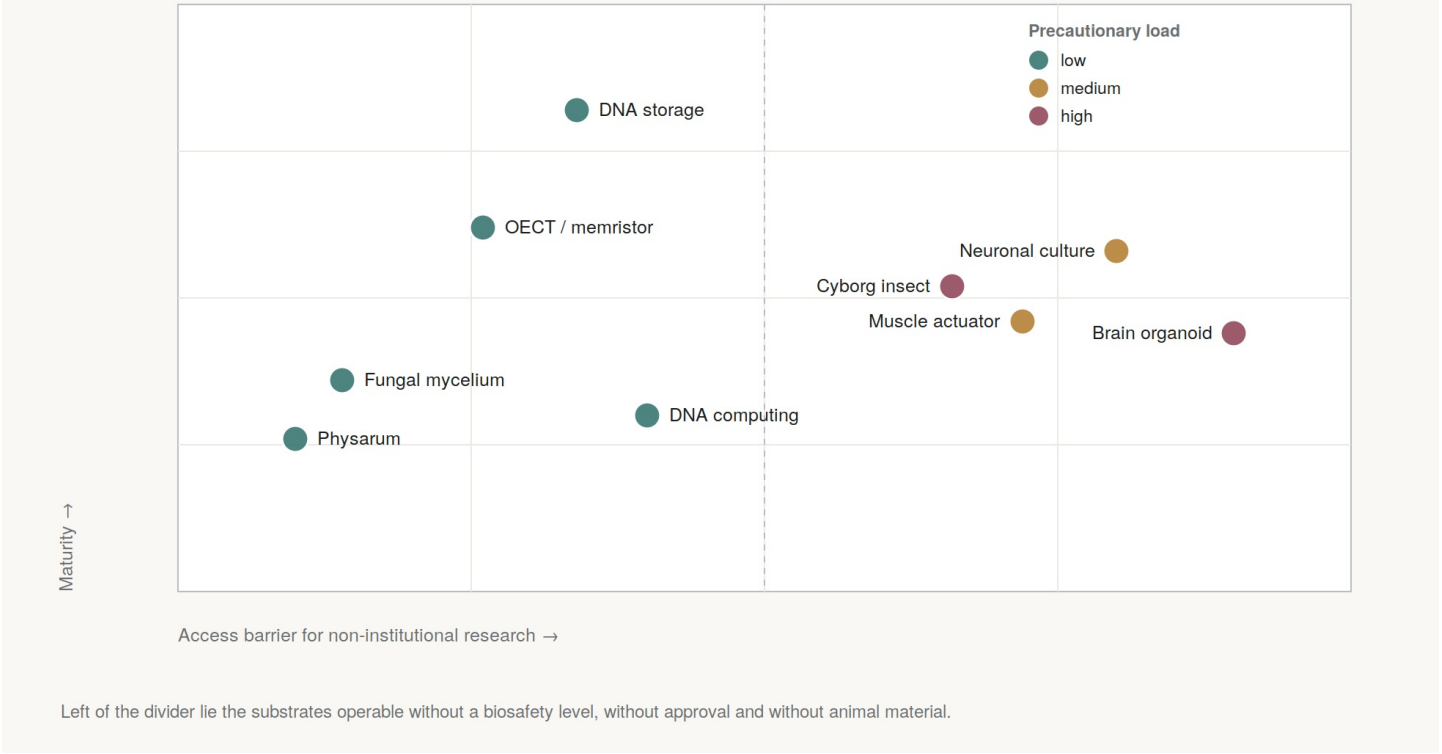


Fig. 2 — Substrate map: maturity against access barrier, colour encodes ethical precautionary load (author’s classification, not a measurement).

The column “animal-free achievable” is not standard in the literature and is introduced here; its justification is approach N1 in section 8.

3 State of the art

3.1 Neuronal wetware

Platforms. Two commercial routes exist.

Feature	Cortical Labs CL1	FinalSpark Neuroplatform
Location	Melbourne (AU)	Vevey (CH)
Substrate	hiPSC-derived cortical neurons on a planar array	forebrain organoids, approx. 500 µm diameter
Electrodes	59 per unit [S]	8 per organoid, 4 organoids per MEA, up to 4 MEAs [P]
Capacity	approx. 800,000 neurons [S]	16 organoids, approx. 160,000 neurons [S]
Sampling	sub-ms output latency [S]	Intan RHS, 30 kHz, 16 bit [P]
Service life	up to approx. 6 months [S]	up to approx. 100 days electrophysiologically active [P]
Access	purchase approx. USD 35,000; rack tier approx. USD 20,000/unit; cloud approx. USD 300/week [S]	remote via Python; free slots by open call, otherwise subscription [S]
Power draw	30-unit rack approx. 850–1000 W [S]	no reliable figure
Deployment	first 115 units announced from summer 2025 (trade press) [S]	operating since 15 May 2024 [S]
Funding	USD 10 m round including In-Q-Tel (intelligence-affiliated venture investor); dated 2023 or 2025 depending on source [S]	no reliable figure

Demonstrated computation. The state of the art is more modest than market communication suggests, but not nil.

Demonstration	System, source	Result	Status
Braille recognition; tactile sensor data as stimulation patterns across eight electrodes	Neuroplatform; Bristol, Ward-Cherrier/Liu, arXiv:2508.20850	61 % classification accuracy with one organoid, 83 % with a three-organoid ensemble	[P] preprint (v2, 02/2026), no journal version
Reservoir-style speech and equation tasks	organoid-silicon composite (Brainware, Indiana University)	reduced training time relative to purely digital comparators reported	[S]
Pong under closed-loop feedback	DishBrain (2022)	stimulus-dependent change of activity; sentence vocabulary criticised as overreaching in follow-up literature	[S]
Digital twins	Neuroplatform data; Ulster, Wong-Lin, 2026	models reproduce firing rates and oscillations	[S]

Maturation and vascularisation are the two physiological bottlenecks. Without vascular supply organoids form a necrotic core, which limits size and maturation [P]. Vascularisation approaches:

Approach	Principle	Status
Endothelial co-culture	introducing endothelial cells into the organoid culture	[P]
ETV2 overexpression	induction of endothelial cells (genetic modification)	[P]
Fusion with vascular organoids	assembloid of neural and vascular organoid	[P]
Perfusion chips	perfusion in a microfluidic carrier	[P]
Meshed micro-vessels from two-photon printing	3D-printed porous tubes with approx. 20 µm sidewall pores	[P]

Timeline: a paper dated 19 Aug 2026 shows that under suitable conditions organoids track a multi-year developmental clock and express features of later brain-development stages [P] (Faravelli, Antón-Bolaños et al., *Nature*, doi:10.1038/s41586-026-10877-x). This shifts the maturation-limit question without removing it.

3.2 Non-neuronal living substrates

Fungal memristors. Shiitake mycelium (*Lentinula edodes*), dehydrated and wired, shows pinched hysteresis, i.e. memristive behaviour. Reported: 95 % memristive fidelity at 5 Vpp/10 Hz and 90 ± 1 % up to 5.85 kHz, with samples remaining functional after dehydration [P] (LaRocco et al., *PLOS One*, doi:10.1371/journal.pone.0328965). Radiation resistance is mentioned there only in the discussion as an argument for aerospace use; no primary study on it has been identified [0].

Fungal logic. Boolean and electrical gates in fungal colonies have been documented since 2020/2021 [P] (Adamatzky, Beasley et al.), largely from one research group and not broadly reproduced independently; reading fungal spiking as “language” is contested in the literature and is not adopted here [P]. Switching times are in the seconds range; these

systems are not intended to replace digital logic but to fuse sensing and computation in the substrate itself.

Slime mould. *Physarum polycephalum* produces approximate solutions to network optimisation problems; sensing and computing devices based on *Physarum* come predominantly from one laboratory (Unconventional Computing Laboratory, UWE Bristol; EU project PhyChip); no reliable device count is documented [0]. The link to kognition-ohne-zentrum (≥0393) is substantive, not merely thematic: the substrate computes without a central instance.

Assessment. This class is inferior to neuronal wetware in maturity and performance, and clearly superior in accessibility and ethical load. It is the only branch that can be run without approval, without a biosafety level, and without animal material.

3.3 Biohybrid robotics

Actuation. Skeletal muscle delivers precise directed contraction, cardiac muscle delivers autonomous rhythm. Both are built into soft-robotic skeletons [P]. Development lines:

Building block	State	Source (type)
Antagonistic muscle pairs	prevent spontaneous shrinkage, extend service life relative to single muscle	Science Robotics [P]
Biohybrid tendons	raise power-to-weight ratio and modularity of muscle-powered robots	Castro et al., Adv. Sci. 2026, doi:10.1002/advs.202512680; murine C2C12 cells, Matrigel, horse serum — under L2 referenced only [P]
Muscle-tendon bioprinting	interdigitated myotendinous junction, computationally optimised muscle geometry	PMC12266124 [P]
Neural reservoir control of a biohybrid arm	control of a soft biohybrid arm through a neural reservoir	PNAS 2026, doi:10.1073/pnas.2522094123 [P]
eBibots	neurons, muscle, biomaterial and microelectronics integrated in one device	npj Robotics review [P]
Soft electronics as interface	resolves the mechanical impedance step between tissue and rigid control	npj Robotics 2026 [P]

Documented limit: fatigue. At four contractions per second over 30 minutes performance drops measurably; at one contraction per second it does not [S]. The final version of the tendon paper reports fatigue tests over more than 7000 cycles; the four-versus-one comparison is not found there [0]. The mechanism is open [0].

Cyborg insects. Terrestrial cyborg insects have been documented since 1997; steering is by stimulation at the antennal bases, readout by probes implanted in the antennal lobe. Reported values: >85 % steering success, 92.8 % static odour recognition, 84.8 % during locomotion [P] (Huang et al., Adv. Mater. Technol. 2025, doi:10.1002/admt.202501158; funding source of this paper not established). The Sniffbot (2026) mounts a locust antenna plus miniaturised electrophysiology on a vehicle and localises odours in still air faster than metal-oxide sensors [P] (bioRxiv 10.64898/2026.02.17.706375).

For context: a substantial part of this line is funded through naval research grants and explicitly aimed at explosives detection. Section 7 covers the resulting exclusion decision.

3.4 Nanobiology

Branch	State	Marker
DNA origami structures	sub-nanometre placement of proteins, nanoparticles and small molecules at programmed binding sites	[P]
Stimulus-responsive nanostructures	shape change, cargo release or mechanical work on pH, temperature, light or biomarker cues; aptamer-gated opening	[P]
Autonomous DNA motors	bipedal non-bridge-burning motor on an origami track, directional travel including 90° turns in a single step	[P] (Sci. Adv., doi:10.1126/sciadv.adi8444)
Protein / peptide origami	de novo folding as a design discipline alongside DNA origami	[P]
DNA data storage	commercial services and cards available; the bottleneck is synthesis rate, not density	[S]

Practical access is comparatively good here: oligonucleotides can be ordered commercially, design tools (caDNAno, oxDNA) are open, but validation requires AFM or gel electrophoresis.

3.5 The semiconductor side as a yardstick

Without this comparison the wetware efficiency claim cannot be checked.

System	Energy per event	Frequency	Marker
Biological synapse	approx. 1-100 fJ per synaptic event (range merged from estimates)	~1-100 Hz	[P] / [S]
CMOS spiking neuron (28/65 nm)	approx. 1.6-4 fJ per spike	—	[P]
Organic nanowire synapse	femtojoule range per event	—	[P]
OECT neuron (BBL-based)	approx. 175 nJ per spike, reproduces 15 of 20 neuronal features	up to 100 Hz	[P]
Memristor crossbar (SNN)	analogue, event-driven; wide spread in vendor figures	kHz-MHz	[S]
Fungal memristor	not cleanly measured	up to 5.85 kHz	[O]

Six to eight orders of magnitude, depending on the reference value, separate the biological synapse (fJ) from the organic artificial neuron (nJ); CMOS spiking neurons, by contrast, already operate in the femtojoule range. The testable gap therefore runs between device classes, not between “biological” and “technical”. The comparison with a data centre additionally conflates substrate level and system level.

The three values measure different events: the organic figure is per neuron spike of a single device, the biological figure per synaptic event (not per action potential; for a whole action potential the cortical energy budget gives about 7×10^8 ATP per neuron [P]), the CMOS figure per spike of an optimised isolated circuit at very low supply voltage. Chip level is higher (picojoules per synaptic operation, in order of magnitude). A breakdown of life support against computation energy for organoids has not been published; the system power figures in circulation are vendor claims [S].

4 Bottlenecks

No.	Bottleneck	Substrates affected	Core of the problem
EP1	Oxygen and nutrient diffusion	organoids	necrotic core beyond a few hundred µm; limits size and maturation
EP2	Service life	organoids, neuronal cultures	approx. 100 days to 6 months; every series restarts biologically
EP3	Electrode count and charge balance	all B3 substrates	8-59 electrodes against 10^5 - 10^6 cells; charge balancing limits stimulation duration
EP4	Missing learning rule	neuronal wetware	no reliable training procedure equivalent to backpropagation; free-energy and reservoir approaches are approximations
EP5	Information density	organoids	order of 1 bit per organoid as the baseline; increases are a stated goal, not an achieved state [S]
EP6	Matrix reproducibility	all organoid culture	batch variance of animal-derived matrices; see N1
EP7	No error model	all living substrates	no established separation of noise, drift, cell death and signal
EP8	Mechanical impedance step	biohybrids	soft tissue against rigid actuation and electronics
EP9	Fatigue	muscle actuators	performance drop at high repetition rate, mechanism open
EP10	Synthesis rate	DNA computing and storage	writing dominates latency, not reading

Bottleneck EP4 is the structurally hardest. As long as no robust learning rule exists, every wetware application is either a reservoir with a digital readout classifier — in which case the intelligence sits in the classifier — or a demonstration of stimulus-response differences.

5 Audit of common claims

Claim	Origin	What is actually shown	Status
“Biological neurons are a million times more energy-efficient”	platform operators	comparison of a human brain’s power draw with a data centre’s; different system boundaries, no common task, life-support peripherals not counted	[O] — not sustainable as a comparison
“Neurons displayed sentience in the game”	DishBrain publication 2022	stimulus-dependent change of activity under closed-loop feedback	[O] — terminology overreaching, criticised in follow-up literature

“First code-deployable biological computer”	vendor marketing	a working interface with programmatic access	[S] — accurate as a product statement, empty as a performance statement
“Organoids cannot be conscious”	ISSCR guidelines 2021	classification as category 1A, exempt from specialised oversight, justified by absence of biological evidence	[P] — 2021 guideline position; the 2025 update concerns embryo models only, organoids remain in 1A; repeatedly criticised as premature in 2025/26
“Brain organoids need complexity limits”	PR China ethics guidelines for organoid research, 29 April 2025	binding national framework with monitoring and complexity requirements	[S] — secondary account, original text not checked
“Organoids will foreseeably become conscious”	counter-position (<i>Patterns</i> 2025)	argument that dismissing the possibility is unjustified if other maturation advances are accepted	[S] — plausibility argument, not proof
“Fungal memristors reach 90 % accuracy at 5.85 kHz”	PLOS One 2025	memristive fidelity to the expected I-V behaviour, not classification accuracy on a task	[P] — correct, but frequently misread

The last row exemplifies a pattern: the same percentage means characteristic-curve fidelity, classification quality or control success rate depending on context. Citations must carry the referent.

6 ρ/δ analysis (instance of FORSCH-0083)

Who carries the risk (ρ), who holds disposal (δ)?

No.	Risk bearer ρ	Disposal holder δ	Asymmetry
A1	Cell donors	platform operators, cell line banks	the line outlives the consent; downstream use for computation was mostly unforeseeable at donation
A2	The substrate itself, if morally relevant	operators and users	decisions on maturation time, stimulation regime and termination sit entirely on the disposal side
A3	Non-institutional researchers	BSL-2 infrastructure, ethics committees, vendors	access depends on rooms and legal form, not competence; price threshold plus waiting list plus biosafety level act cumulatively
A4	The public	vendors holding interpretive authority over technical terms	terms such as sentience, intelligence and learning are set in market communication and migrate from there into regulatory debate
A5	Animals upstream in the supply chain	matrix and media manufacturers	the animal component sits in Matrigel, sera and supplements, i.e. below the visibility threshold of the application
A6	Those regulated later	early adopters, funding logics	defence pre-funding shapes which capabilities mature first, and thereby the starting state of any later civilian rule

A3 is where the asymmetry becomes technical rather than rhetorical. The occupational-safety grounds for BSL-2 with human cell material are real: contamination risk for the worker, cross-contamination, disposal of human biological material. Equally real is that an infrastructure monopoly follows from it which is not derived from the level of risk but has grown historically. The countermeasure is not rule circumvention but building shared laboratory infrastructure and working the approval-free substrate classes consistently. A5 is the weakest-covered point in the literature and the starting point of approach N1.

7 Guardrails for this strand

Four rules that follow from existing commitments and are applied here to specific approaches.

L1 — No military, no weapons, no defence. In this field the affected lines are primarily cyborg insects and biohybrid sensing: explosives detection with locust antennae, remote-controlled insects for reconnaissance, nano-tattoo steering. The exclusion does not cover the underlying sensory physiology or odour coding as such. It covers setups whose purpose is detection of ordnance, reconnaissance or targeting. The civilian parallel application — gas leak localisation, environmental monitoring — is permissible, but must be kept separate in purpose, publication form and funding source, otherwise the exclusion has no effect.

L2 — No animal material. The exclusion bites before the laboratory animal, namely in consumables. Affected: Matrigel and related matrices (murine sarcoma extract), foetal calf serum, animal-derived serum substitutes, animal antibodies in characterisation, insect preparations in biohybrid sensing, animal-derived skeletal and cardiac muscle cells in actuation. Approach N1 follows from this, and from that in turn that muscle-driven biohybrids is not pursued practically in this strand, only referentially. The same applies to remote platforms whose culture chain contains animal components; their use requires a written statement from the operator (see V6).

L3 — Precaution regarding the substrate. While the consciousness question is open, a precautionary regime applies that does not wait for an answer. Operationally: no stimulation regimes built on aversion and avoidance where alternatives exist; no combination of nociceptor differentiation with closed-loop feedback; a documented maturation ceiling per series; a termination protocol fixed in advance and published with the work; no adoption of sentence vocabulary without a measurand.

L4 — Provenance and consent. Cell lines only with documented consent that covers the computational purpose. Where consent does not cover it, this must be recorded in the work and not disposed of by reference to anonymisation.

8 Novel approaches

Five proposals that the surveyed literature does not occupy, or occupies only marginally.

N1 — An animal-free wetware stack

Observation. Organoid research is routinely presented as a replacement for animal experiments. The culture chain nevertheless still contains animal components. The standard matrix Matrigel is murine sarcoma extract; more than 14,000 publications rest on it, while the most common xeno-free whole-matrix alternative is cited in the low double digits [P] (Wolff et al., *Adv. Sci.* 2025, doi:10.1002/advs.202508734; count date and database not stated there).

Available building blocks.

Layer	Animal-containing standard	Animal-free alternative	Evidence
2D coating for hiPSC	Matrigel	recombinant vitronectin (XF)	maintains pluripotency, enables enzyme-free passaging [P]
3D matrix	Matrigel	fibrin hydrogel; fibrin-laminin-511 chimera (3D expansion of hiPSC, doi:10.1016/j.matbio.2025.10.003; one co-author holds a stake in the matrix manufacturer); recombinant laminin-511 fragment; VitroGel ORGANOID (synthetic polysaccharide); PeptiMatrix, PuraMatrix (synthetic peptides); GrowDex (wood nanocellulose)	equivalence documented for vascular organoids [P] ; for cerebral organoids vendor comparison only, independent replication missing [0]
Medium / supplements	FBS, animal supplements	chemically defined xeno-free systems	available, batch comparison for brain organoids open [0]
Characterisation	animal antibodies	recombinant antibodies, mass spectrometry	available [S]

Gap. For cerebral organoids operated as a computing substrate, no published end-to-end animal-free chain with an electrophysiological endpoint exists. What exists are individual comparisons for vascular, intestinal and tumour organoids. A preliminary search (09/2026) confirms the finding; the systematic search with a documented strategy is outstanding (verification item 31).

Proposal. A systematic comparison with an electrophysiological endpoint: identical cell line, four matrix conditions, endpoints firing rate, burst rate, network synchrony, maturation trajectory, batch spread. This approach is immediately publishable as a review and collaboration-ready as bench work, because it is useful to any organoid laboratory independently of the computing purpose. It is at the same time the condition under which wetware work in this strand is compliant with its own rules at all.

N2 — A substrate ethics gradient instead of a binary decision

The debate runs binary: organoids either can be conscious or cannot. What would be operationally useful is a gradient over measurable proxies that scales requirements rather than switching them. Candidate axes: cell count; fraction of differentiated neurons; presence of nociceptive cell types; network synchrony; maturation duration; presence of closed sensorimotor feedback; multi-regionality (assembloid). The gradient claims no measurement of consciousness. It ranks

setups by precautionary need and makes requirements justifiable before a threshold can be established. Compatible with the PIS-12 scale logic from FORSCH-0333.

N3 — Spectro-temporal coding as a wetware benchmark

The wetware task with sensory grounding demonstrated so far is a tactile classification across eight electrodes. Audio is the obvious unoccupied neighbouring case and methodologically more favourable: the input signal is temporally structured by nature, feature extraction (filter bank, onset, modulation spectrum) is established, and hard digital baselines exist. Proposed benchmark in three stages — onset discrimination, timbre classification at constant pitch, rhythm pattern recognition — each against a reservoir baseline of equal readout complexity. The core of the evaluation is showing that discriminability arises in the substrate and not in the classifier: an identical classifier on shuffled data must fail.

N4 — A p/6 access index for biocomputing platforms

A reproducible index over five axes: monetary threshold, waiting time, jurisdiction, required biosafety level, data return rights. Applicable to any platform, publishable as a table with a methods section, and suited to lift asymmetry A3 from section 6 out of the anecdotal. The index measures not quality but the distribution of disposal.

N5 — Terminological correction B1/B2/B3

The three-level distinction in section 1 is itself a result. German-language technical and funding literature uses “bionics” for all three levels, which systematically misdirects calls, curricula and project plans: B1 competences are budgeted for B3 undertakings. A short position paper with a decision table can be run as a sub-paper to this work.

9 Connections

Cross-references within the FORSCHUNG strand. Register check of 2026-09-22; numbers provisional where assigned.

Related work	Connection	Character
FORSCH-0364 substrat-und-erleben	supplies the consciousness axis on which L3 and N2 rest	theoretical, direct
FORSCH ≥0393 kognition-ohne-zentrum	<i>Physarum</i> and fungal networks are substrate evidence for the thesis argued there	theoretical, direct
FORSCH-0083	p/6 section 6 as a domain instance	structural
bewusstsein-verhaeltnis-cluster	consciousness as relation rather than possession; to be tested against the threshold logic that L3 and N2 presuppose	theoretical, to be tested
FORSCH-PROV0420 messbarkeit-rahmentheorie	reconstructability from few measurement channels; formal frame for EP3 and open question 5	methodological, direct
FORSCH-PROV0421 skelett-mineralisierung-membran	membrane biology as the basis of bioelectric signal conduction	subject-matter, indirect
biochemie-zentrales-dogma	biochemical basis for DNA computing and storage (3.4, V7)	subject-matter, indirect
kontrollierte-umgebungen	clean-room and laboratory environment as precondition for V8	subject-matter, direct
elektronische-klangerzeugung	filter bank and feature extraction as precondition for N3 and V6	technical, direct

Application fields without strand reference.

Field	Connection	Character
Wearable gas sensing (e-nose)	biological olfaction as a yardstick for sensor arrays; animal-free variant via receptor-based sensing instead of insect preparations	technical, indirect
Peripheral manufacturing (additive, laser, textile)	incubator housings, perfusion holders, MEA mounts, Faraday cages, drying moulds for mycelium samples	manufacturing, immediate
Data-sovereign health data	donor material as personal data; zero-knowledge logic applicable to cell-line provenance	conceptual
High-altitude exposure (stratospheric balloon)	radiation resistance of dehydrated fungal memristors as a testable payload case; the underlying claim so far lacks a primary study	experimental

The peripheral-manufacturing row is the most robust: the competence at hand lies in the peripherals, not the substrate. That is not a limitation but the point of greatest leverage, because peripherals in this field are consistently expensive, proprietary and poorly documented. This work makes no links to commercial applications.

10 Experimental programme

Eight experiments ordered by rising access barrier. Cost figures are orders of magnitude for a first build, excluding labour.

The descriptions state question, principle, measurand, controls and cost order of magnitude. They deliberately omit process parameters: drying temperatures and durations, layer thicknesses, deposition and patterning parameters, mixing ratios, suppliers and part numbers are not given here. This withholds nothing needed to assess the work — the finding and the argument stand complete in the free part, and refuting them needs no bill of materials. It separates finding from replication.

ID	Experiment	Tier	Cost range	Legal status	Ethics status	Animal-free
V1	Mycelium memristor bank	0	EUR 500-1500	no restriction	unproblematic	yes
V2	Physarum reservoir	0	EUR 200-600	no restriction	unproblematic	yes
V3	Open MEA hardware	0	EUR 1500-4000	no restriction	unproblematic	yes
V4	Comparison of animal-free matrices (desk tier)	0	labour	no restriction	unproblematic	yes
V5	Actuation without animal cells	0	EUR 300-1000	no restriction	unproblematic	yes
V6	Spectro-temporal coding on an organoid platform	1	labour, any platform fee	operator's jurisdiction	document platform ethics status in advance	open, operator statement required
V7	DNA coding with physical endpoint control	2	EUR 300-2000	no restriction for synthetic oligos	unproblematic	yes
V8	Wetware with own culture	2	open	BSL-2, legal status open	precautionary protocol L3	only with an N1 chain

Tier 0 — approval-free, animal-free, workshop

V1 — Mycelium memristor bank. *Question:* How do memristive characteristics scatter across substrate, species, degree of drying and electrode material? *Setup:* Grain or hemp substrate, edible-mushroom culture, stainless-steel and PEDOT:PSS-coated ITO electrodes, defined drying stages, I-V curves over frequency and amplitude. *Measurand:* Area and symmetry of the pinched hysteresis loop, retention over cycles, sample-to-sample spread. *Contribution:* The published work shows feasibility on few samples. A scatter study with a standardised drying protocol and an open dataset is missing. *Requirements:* Function generator, oscilloscope or DAQ card, humidity chamber. EUR 500-1500. *Law:* no restriction. *Ethics:* unproblematic.

V2 — Physarum reservoir. *Question:* Does the network topology serve as a reservoir for a temporal classification task? *Setup:* Agar plate, oat flakes as attractors, electrode grid, readout of the resistance matrix over time, digital readout classifier. *Measurand:* Separability against a random baseline and against an echo-state network with equal readout size. *Contribution:* Direct evidence for the thesis of ≥ 0393 . German-language literature effectively absent. *Requirements:* EUR 200-600. *Law/ethics:* unproblematic.

V3 — Open MEA hardware. *Question:* Can a transparent MEA be produced to sufficient quality with workshop means? *Setup:* ITO-coated glass, patterning, PEDOT:PSS deposition on contact pads, carrier PCB, connection to an Intan headstage, acquisition through the Open Ephys chain; validation initially on fungal and *Physarum* samples, not cell culture. *Measurand:* Per-electrode impedance, noise floor, crosstalk. *Contribution:* The open build instructions (transparent MEA; OpenMEA) are published but rarely rebuilt independently. A documented rebuild with a deviation report is a contribution in its own right and the precondition for everything further. *Requirements:* EUR 1500-4000 depending on headstage. *Law/ethics:* unproblematic.

V4 — Systematic comparison of animal-free matrices (desk tier). *Question:* Which xeno-free matrices are documented for neural 3D culture with an electrophysiological endpoint, and which are merely asserted? *Setup:* Full literature search, extraction grid (matrix, cell type, endpoint, comparator arm, batch count, funding, stakeholder interest), grading levels. *Result:* A publishable review plus a draft bench protocol for N1. *Requirements:* labour only. *Law/ethics:* unproblematic.

V5 — Actuation without animal cells. *Question:* What actuation performance is reachable with hygromorphic and mycelium-based composites relative to muscle actuators? *Setup:* Moisture-driven fibre composites and mycelium composites, 3D-printed anisotropic carriers, measurement of stroke, force, cycle count, time constant. *Measurand:* Work per cycle, power density, fatigue, comparison against published muscle values. *Contribution:* The comparison is not drawn in the biohybrid literature because the communities are separate. A negative result is equally publishable. *Requirements:* EUR 300–1000, mostly existing manufacturing.

Tier 1 — remote access, external infrastructure

V6 — Spectro-temporal coding on an organoid platform (N3). *Question:* Do organoids produce distinguishable response patterns to spectro-temporally coded audio stimuli, and does the separability reside in the substrate? *Setup:* Local feature extraction (filter bank, onset detection, modulation spectrum), mapping onto eight stimulation channels, recording through the platform API, offline evaluation. Three stages: onset, timbre at constant pitch, rhythm patterns. *Controls:* identical classifier on temporally permuted stimuli; identical classifier on blank-channel recordings; reservoir baseline of equal readout complexity. *Measurand:* Classification accuracy against all three controls, discriminability per stage. *Contribution:* An unoccupied modality, drawing on existing audio competence, directly compatible with the published Braille protocol. *Access:* apply for a free slot through the open call, otherwise subscription. The platform's ethics status is to be documented in advance, not presupposed. *Requirements:* labour plus any platform fee. *L2 reservation:* The platform's culture chain (matrix, medium, supplements) must be queried in writing before applying. If it contains animal components, V6 cannot be run under guardrail L2; the N3 benchmark then runs on the animal-free reservoirs from V1 and V2.

Tier 2 — collaboration-dependent

V7 — DNA coding with physical endpoint control. *Question:* How does a self-designed coding scheme with error correction behave under real synthesis and real readout? *Setup:* Local encoder/decoder, short oligos ordered commercially, readout via a sequencing service or a nanopore collaboration. *Measurand:* Raw per-base error rate, recovery rate after correction, cost per kilobyte. *Requirements:* EUR 300–2000 depending on length and readout.

V8 — Wetware with own culture. Only after V1–V6 and only under three conditions: a documented laboratory collaboration at the appropriate biosafety level, a matrix chain per N1, a precautionary protocol per L3. Without all three the step is permissible neither legally nor under the strand's own rules.

Recommended order: start V4 and V1 in parallel. V4 is pure desk work with an immediate publication target; V1 produces the first own measurement series and generates the hardware need that V3 then covers. V6 is applied for only once V3 shows the evaluation chain works and the platform operator has confirmed that the culture chain is animal-free; otherwise the N3 benchmark runs on the reservoirs from V1 and V2.

11 Open questions

1. Does a learning rule exist for dissociated and organoid networks that does not reduce to a reservoir plus digital readout classifier? [0]
2. What is the actual energy demand of a wetware system including life support, per task solved? Reliable figures are missing. [0]
3. Does the multi-year developmental clock (*Nature*, 08/2026) shift the precautionary threshold, and if so, measured against what? [0]
4. Are xeno-free matrices electrophysiologically equivalent for cerebral organoids? Documented for vascular organoids, open here. [0]
5. At what electrode density does the readout side move from sampling to state estimation? [0]
6. Can radiation resistance of dehydrated fungal memristors be confirmed under real high-altitude exposure? [0]
7. Which Austrian and Union provisions apply specifically to human iPSC culture without genetic modification, and where does the analogy to tissue-safety law end? — preliminary search 09/2026 (not legal advice): for culture without genetic modification in a non-clinical laboratory, worker protection (ASchG § 40(5), Ordinance on Biological Agents) and data protection (GDPR Art. 9) are in the foreground; by their wording the Tissue Safety Act and the Genetic Engineering Act do not apply, the latter however does with any genetic modification. Risk group, derivation phase and consent remain open in the individual case; to be confirmed by a qualified expert before any wetware work. [0]
8. Is the culture chain of the available remote organoid platforms (matrix, medium, supplements) animal-free? Public operator information does not name matrix, serum or supplements [5]. Without a written statement from the operator, V6 cannot be run under guardrail L2. [0]

12 Sources

Selection of load-bearing references. Full verification: see the verification list in [werk/](#).

Short reference	Subject	Identifier	Status
Ward-Cherrier, Liu et al.	Braille coding with organoids, 61 %/83 %	arXiv:2508.20850	[P] preprint, v2 02/2026
LaRocco et al. 2025	shiitake mycelium memristors	doi:10.1371/journal.pone.0328965	[P]
Faravelli, Antón-Bolaños et al. 2026	multi-year developmental clock in organoids	doi:10.1038/s41586-026-10877-x	[P]
Gazzola et al. 2026	neural reservoir control of a biohybrid arm	doi:10.1073/pnas.2522094123	[P]
Wolff et al. 2025	Matrigel replacement, barriers and alternatives	doi:10.1002/advs.202508734	[P]
Scientific Reports 2025	animal-free matrices for hiPSC vascular organoids	doi:10.1038/s41598-025-20091-w	[P]
<i>Science Advances</i>	autonomous DNA motor on an origami track	doi:10.1126/sciadv.adi8444	[P]
Adamatzky et al. 2020/2022	Boolean and electrical gates in fungal colonies	Biosystems 193:104138; Log. Univers. 16(4)	[P]
Hartung, Smirnova et al. 2023	organoid intelligence programme article	doi:10.3389/fsoci.2023.1017235	[P]
Jordan et al. 2024	Neuroplatform, open remote access	doi:10.3389/frai.2024.1376042	[P]
<i>Patterns</i> 2025	counter-position to consciousness scepticism	S2666-3899(25)00213-2	[P]
Asia Pacific Neuroethics WG 2026	consensus recommendations on brain organoids	doi:10.1007/s41649-025-00398-6	[P]
Le et al. 2026	review of terrestrial cyborg insects	doi:10.1002/aisy.202501119	[P]
Shvil, Ayali et al. 2026	Sniffbot, biohybrid odour localisation	bioRxiv 10.64898/2026.02.17.706375	[P] preprint
npj Robotics 2025/2026	biohybrid actuation, soft electronics	doi:10.1038/s44182-025-00049-w; ...-026-00072-5	[P]
ACS Nano	3D-printed meshed micro-vessels for organoids	doi:10.1021/acsnano.4c07844	[P]
JACS Au 2026	DNA origami, state and limits	doi:10.1021/jacsau.5c01315	[P]
OECT review 2026	OECT neurons, 175 nJ/spike	PMC12902651	[P] (journal DOI open)
Castro et al. 2026	biohybrid tendons, 109.6 nW/mg	doi:10.1002/advs.202512680	[P]
Huang et al. 2025	insect probe, steering and odour recognition	doi:10.1002/admt.202501158	[P]
Taniguchi et al. 2025	fibrin–laminin-511 chimera, hiPSC in 3D	doi:10.1016/j.matbio.2025.10.003	[P]
ISSCR 2021	guidelines, organoids category 1A	Stem Cell Reports S2213-6711(21)00263-0	[P]
Xu et al. 2016	organic synapse, fJ reference values	doi:10.1126/sciadv.1501326	[P]
arXiv 2024	CMOS spiking neuron 1.6 fJ/spike	arXiv:2408.07734	[P] preprint

Not cited: vendor blogs as evidence for performance claims, news aggregators, social media posts. Where vendor figures appear in the text they are marked [S] and identified as statements by a stakeholder.

13 Glossary

Term	Meaning in this work
Assembloid	fusion of several region-specific organoids, or organoid plus foreign cell type
Biohybridics (B2)	technical system with a living component as actuator, sensor or controller
hiPSC	human induced pluripotent stem cells
MEA	microelectrode array
Memristance	resistance-like device behaviour with history dependence, recognisable by a pinched hysteresis loop
Reservoir computing	approach in which a fixed dynamical system generates features and only the readout layer is trained
Substrate computing (B3)	the computation takes place in the biological medium
Wetware	living neuronal networks as a computing medium
Xeno-free	free of animal-derived components throughout the culture chain

ρ/δ

ratio of risk bearing to disposal power (FORSCH-0083)