Journal of Experimental Psychology:
Human Perception and Performance

ISSN: 0096-1523

2025, Vol. 51, No. 5, 543–546
https://doi.org/10.1037/xhp0001310

50TH ANNIVERSARY ARTICLE

The Past, Present, and Future of Relation Perception

Alon Hafri[1] and Liuba Papeo[2, 3]
[1] Department of Linguistics and Cognitive Science, University of Delaware
[2] Institute of Cognitive Sciences "Marc Jeannerod"–UMR 5229, Centre National de la Recherche Scientifique, Bron, France
[3] Institute of Cognitive Sciences "Marc Jeannerod", Université Claude Bernard Lyon 1

What kind of information does perception represent, and in what format? How does perception interface with higher-level cognitive systems for thinking, reasoning, and language? Questions like these motivated Green and Hummel in their seminal 2006 article in *Journal of Experimental Psychology: Human Perception and Performance* (*JEP:HPP*), "Familiar Interacting Object Pairs Are Perceptually Grouped." At first glance, the subject matter of Green and Hummel's article appears quite simple and mundane: actions like pouring coffee, cutting bread, or unlocking a door. Yet hidden at the core of such everyday routines are specific functional relationships between objects, such as a carafe and a mug, a knife and a loaf, or a key and a lock. Green and Hummel's article was a turning point in a long but sparse tradition of research that had considered such relations from a vision-science perspective (e.g., Scholl & Tremoulet, 2000; Ullman, 1984), as it steered many researchers—ourselves included—to explore questions in the burgeoning field now known as "relation perception." This field advances the idea that, beyond objects, features, and locations, the visual system spontaneously or automatically extracts and represents relations—properties that specify interactions or connections between objects, rather than each object's individual characteristics. In this perspective article, we outline new aspects of human visual perception that have been the focus of this field and the major outstanding questions that remain.

While relations had long been emphasized in work on language and cognition (e.g., Landau & Jackendoff, 1993; Miller & Johnson-Laird, 1976; Talmy, 1985; inter alia), Green and Hummel recognized that the visual system might play a crucial role in inferring relational information from scenes (Green & Hummel, 2003). Indeed, the connection between perception and cognition is what initially drew us to their work. While studying issues related to the representation of events in language (Trueswell et al., 2012) and semantics (Papeo et al., 2012, 2015), we independently stumbled upon Green and Hummel's research, which led us to suspect that cognitive event representations might have precursors in visual processing.

In Green and Hummel's (2006) article, four experiments showed that functional relations between objects—the spatial arrangement of two familiar objects relative to one another—affected object identification. In a word picture verification task, adult participants saw an object label (e.g., "glass"), followed by a central line drawing of one object for 50 ms, a 50-ms blank, and then another object to the left or right for 50 ms. Participants had to report whether the second object matched the label. The key manipulation was the spatial positioning of the objects: they were either arranged to suggest a common goal/function (e.g., a pitcher tilted toward a glass) or not (e.g., a pitcher tilted away). Results showed that object identification was more accurate when the objects were in a functional configuration. Follow-up experiments indicated that this effect was exquisitely sensitive to timing (disappearing at a stimulus-onset asynchrony of 250 ms), and was independent of attentional cueing (arising regardless of object order) and subjective expectations (remaining even when the label followed the objects). Green and Hummel's work suggested that as soon as observers saw the objects, they also saw the relations between them, provoking the intriguing idea that the representation of higher-level relations—the foundation of human thinking and reasoning—is rooted in perception.[1]

Green and Hummel's seminal article has inspired a wealth of empirical literature, much of which has appeared in *JEP:HPP* (e.g., Nah & Geng, 2022; O'Donnell et al., 2018; Papeo & Abassi, 2019; Riddoch et al., 2011; Roberts & Humphreys, 2010; S. Xu et al., 2015; Yoon et al., 2010), and has been highlighted in several review articles on this topic (Hafri & Firestone, 2021; Kaiser et al., 2019; Oliva & Torralba, 2007; Papeo, 2020; Peelen et al., 2024). Using the tools of vision science, researchers in this field have begun to unveil the precise ways that the visual system represents relations. For example, while

Isabel Gauthier served as action editor.

Liuba Papeo https://orcid.org/0000-0003-3056-8679

This research was funded in whole, or in part, by the European Commission (EC) (Grant THEMPO-758473). For the purpose of open access, the authors have applied a CC BY public copyright license to any Author Accepted Manuscript version arising from this submission.

Liuba Papeo was supported by a European Research Council Grant (Project THEMPO-758473).

Liuba Papeo served as lead for conceptualization, funding acquisition, project administration, resources, writing–original draft, and writing–review and editing. Alon Hafri served as lead for conceptualization, funding acquisition, project administration, resources, writing–original draft, and writing–review and editing.

Correspondence concerning this article should be addressed to Liuba Papeo, Institute of Cognitive Sciences "Marc Jeannerod"–UMR 5229, Centre National de la Recherche Scientifique, 67 Boulevard Pinel, Bron 69675, France. Email: liuba.papeo@isc.cnrs.fr

[1] It is worth highlighting that the control manipulation (facing objects away from one another) was key for demonstrating that the experimental effects were due to relational processing per se and not to confounding factors (e.g., the presence of particular objects or the body postures in a social interaction).

early work assigned the encoding of relations (e.g., inside) to effortful visual routines operating "on demand" (when required by the task; e.g., Jolicoeur et al., 1991; McCormick & Jolicoeur, 1992; Ullman, 1984), the recent wave of work shows the automaticity and immediacy characteristic of typical perceptual processes (for color, shape, texture, etc.), at least for certain types of relations (Hafri & Firestone, 2021). Perhaps due to this automaticity and immediacy, certain relational representations afford distinct processing advantages to perceptual processes: familiar configurations of everyday objects (e.g., lamp above table) enhance detection of targets in cluttered scenes (Kaiser et al., 2014), increase memory capacity for objects (Gronau & Shachar, 2015; Kaiser et al., 2015; O'Donnell et al., 2018), and diminish the effects of visual extinction in patients (Riddoch et al., 2011). Similarly, in the social domain, two face-to-face people (seemingly interacting) are more likely to be detected under visual noise than the same individuals facing away from each other (Papeo et al., 2017, 2019; Vestner et al., 2019). These advantages extend broadly across visual processing, from early preattentive stages (Fu et al., 2024; Papeo et al., 2017; Z. Xu et al., 2023) to visual memory (Ding et al., 2017; Paparella & Papeo, 2022; Vestner et al., 2019). Relational representations also appear to be domain-specific, recruiting distinct visual brain areas for encoding relations between animate entities and inanimate objects (Abassi & Papeo, 2022, 2024; Wurm et al., 2017).

Other findings suggest that visual relational information is structured (distinguishing between, e.g., woman pushes man and man pushes woman; Hafri et al., 2018; Papeo et al., 2024; Vettori et al., 2024), categorical (showing greater sensitivity to differences across than within category, e.g., containing vs. touching; Ji & Scholl, 2024; Lovett & Franconeri, 2017), and relatively abstract (applying to different instances of the same relation; Hafri et al., 2024; Papeo et al., 2024). This implies that many perceptual representations of relations are not purely imagistic but share characteristics with a "language-of-thought" (Hafri, 2024; Hafri, Green, & Firestone, 2023; Papeo et al., 2024; Quilty-Dunn et al., 2023), perhaps facilitating the transition from perceptual to cognitive systems (Cavanagh, 2021; Quilty-Dunn, 2020; for empirical evidence see, De Freitas & Alvarez, 2018; De Freitas & Hafri, 2024; Hafri, Gleitman, et al., 2023)—an insight presaged by Green and Hummel (2003) themselves.

A main challenge for this research field is to isolate perception from the rest of cognition. Traditionally it has been assumed that perception primarily represents lower-level content such as motion, color, or texture (Tye, 1997); however, the possibility that perception also represents higher-level relational content implies that the sophistication of a representation's content alone is insufficient for determining whether a representation "counts" as perceptual. Thus, work in relation perception has gone hand in hand with the development of original paradigms (Hafri et al., 2018; Papeo et al., 2017, 2019; Z. Xu et al., 2023) and the delineation of empirical signatures (Hafri & Firestone, 2021; Scholl & Gao, 2013) to isolate perceptual processes from cognitive ones. To the degree that this work has succeeded in placing relational representations in the purview of visual perception, it suggests a reevaluation of the sophistication, computational goals, and representational format of perception. This new work will also have to clarify which levels of visual processing are involved; that is, whether relation representations emerge in mid-level vision (in the form of object files and structures; Pylyshyn, 2007), in high-level vision (where contents such as object and relational categories are specified), or across distinct levels for different aspects of relations.

Stepping back, Green and Hummel's article foreshadowed nearly 20 years of advances in perception research that has made progress in answering some of the questions that motivated their original article. This growing body of work has demonstrated that visual processing furnishes relational representations that are structured, abstract, and uniquely suited to interface with higher level systems of language and thought. In doing so, this research has set the stage for addressing key unanswered questions. For example, are there "primitive" relational categories (e.g., next-to, cause, or socially interact)? If so, how do more complex relational representations develop (e.g., those taking place between more than two entities; Fratino et al., 2022; Yin et al., 2022), and under what conditions are these perceived? Could it be that only some relations, such as those highlighted above, are extracted immediately, automatically, and effortlessly, whereas relation perception in general tends to be slower, deliberate, and effortful (e.g., green is to the left of red; Franconeri et al., 2012; Logan, 1995; Roth & Franconeri, 2012; Ullman, 1984; Yuan et al., 2016)? Or perhaps some relations, even if spontaneous, depend on time-intensive visual routines to extract (e.g., tracing a maze; Wong & Scholl, 2024)? Does acquiring words for relational categories fundamentally alter perceptual representations, or are they relatively insulated from higher-level knowledge and beliefs (Firestone & Scholl, 2016)? Which aspects are shared with our phylogenetic relatives, and which are uniquely human (Goupil et al., 2024; Zanon et al., 2024)? How does the brain accommodate the abstract and structured format of these representations? We believe that relation perception will remain a central topic in *JEP:HPP* for the next 50 years, and we are excited to continue playing a role in this field.

References

Abassi, E., & Papeo, L. (2022). Behavioral and neural markers of visual configural processing in social scene perception. *NeuroImage*, *260*, Article 119506. https://doi.org/10.1016/j.neuroimage.2022.119506

Abassi, E., & Papeo, L. (2024). Category-selective representation of relationships in the visual cortex. *The Journal of Neuroscience*, *44*(5), Article e0250232023. https://doi.org/10.1523/JNEUROSCI.0250-23.2023

Cavanagh, P. (2021). The language of vision. *Perception*, *50*(3), 195–215. https://doi.org/10.1177/0301006621991491

De Freitas, J., & Alvarez, G. A. (2018). Your visual system provides all the information you need to make moral judgments about generic visual events. *Cognition*, *178*, 133–146. https://doi.org/10.1016/j.cognition.2018.05.017

De Freitas, J., & Hafri, A. (2024). Moral thin-slicing: Forming moral impressions from a brief glance. *Journal of Experimental Social Psychology*, *112*, Article 104588. https://doi.org/10.1016/j.jesp.2023.104588

Ding, X., Gao, Z., & Shen, M. (2017). Two equals one: Two human actions during social interaction are grouped as one unit in working memory. *Psychological Science*, *28*(9), 1311–1320. https://doi.org/10.1177/0956797617707318

Firestone, C., & Scholl, B. J. (2016). Cognition does not affect perception: Evaluating the evidence for "top-down" effects. *Behavioral and Brain Sciences*, *39*, Article e229. https://doi.org/10.1017/S0140525X15000965

Franconeri, S. L., Scimeca, J. M., Roth, J. C., Helseth, S. A., & Kahn, L. E. (2012). Flexible visual processing of spatial relationships. *Cognition*, *122*(2), 210–227. https://doi.org/10.1016/j.cognition.2011.11.002

Fratino, V., Colombatto, C., & Ristic, J. (2022). From dyads to triads: Perceptual unity of social groups. *Journal of Vision*, *22*(14), Article 4227. https://doi.org/10.1167/jov.22.14.4227

Fu, Y., Zhou, M., Zhou, J., Shen, M., & Chen, H. (2024). Unconscious prioritization for face-to face people. *Journal of Experimental Psychology: General*, *153*(5), 1268–1280. https://doi.org/10.1037/xge0001556

Goupil, N., Rayson, H., Serraille, É., Massera, A., Ferrari, P. F., Hochmann, J. R., & Papeo, L. (2024). Visual preference for socially relevant spatial relations in humans and monkeys. *Psychological Science*, *35*(6), 681–693. https://doi.org/10.1177/09567976241242995

Green, C., & Hummel, J. E. (2003). Relational perception and cognition: Implications for cognitive architecture and the perceptual-cognitive interface. *Psychology of Learning and Motivation*, *44*, 201–226. https://doi.org/10.1016/S0079-7421(03)44006-1

Green, C., & Hummel, J. E. (2006). Familiar interacting object pairs are perceptually grouped. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(5), 1107–1119. https://doi.org/10.1037/0096-1523.32.5.110

Gronau, N., & Shachar, M. (2015). Contextual consistency facilitates long-term memory of perceptual detail in barely seen images. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(4), 1095–1111. https://doi.org/10.1037/xhp0000071

Hafri, A. (2024). The origins of structured thought in the mind. *Current Biology*, *34*(18), R856–R859. https://doi.org/10.1016/j.cub.2024.07.096

Hafri, A., Bonner, M. F., Landau, B., & Firestone, C. (2024). A phone in a basket looks like a knife in a cup: Role-filler independence in visual processing. *Open Mind*, *8*, 766–794. https://doi.org/10.1162/opmi_a_00146

Hafri, A., & Firestone, C. (2021). The perception of relations. *Trends in Cognitive Sciences*, *25*(6), 475–492. https://doi.org/10.1016/j.tics.2021.01.006

Hafri, A., Gleitman, L. R., Landau, B., & Trueswell, J. C. (2023). Where word and world meet: Language and vision share an abstract representation of symmetry. *Journal of Experimental Psychology: General*, *152*(2), 509–527. https://doi.org/10.1037/xge0001283

Hafri, A., Green, E. J., & Firestone, C. (2023). Compositionality in visual perception. *Behavioral and Brain Sciences*, *46*, Article E277. https://doi.org/10.1017/S0140525X23001838

Hafri, A., Trueswell, J. C., & Strickland, B. (2018). Encoding of event roles from visual scenes is rapid, spontaneous, and interacts with higher-level visual processing. *Cognition*, *175*, 36–52. https://doi.org/10.1016/j.cognition.2018.02.011

Ji, H., & Scholl, B. J. (2024). "Visual verbs": Dynamic event types are extracted spontaneously during visual perception. *Journal of Experimental Psychology: General*, *153*(10), 2441–2453. https://doi.org/10.1037/xge0001636

Jolicoeur, P., Ullman, S., & Mackay, M. (1991). Visual curve tracing properties. *Journal of Experimental Psychology: Human Perception and Performance*, *17*(4), 997–1022. https://doi.org/10.1037/0096-1523.17.4.997

Kaiser, D., Quek, G. L., Cichy, R. M., & Peelen, M. V. (2019). Object vision in a structured world. *Trends in Cognitive Sciences*, *23*(8), 672–685. https://doi.org/10.1016/j.tics.2019.04.013

Kaiser, D., Stein, T., & Peelen, M. V. (2014). Object grouping based on real-world regularities facilitates perception by reducing competitive interactions in visual cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(30), 11217–11222. https://doi.org/10.1073/pnas.1400559111

Kaiser, D., Stein, T., & Peelen, M. V. (2015). Real-world spatial regularities affect visual working memory for objects. *Psychonomic Bulletin & Review*, *22*(6), 1784–1790. https://doi.org/10.3758/s13423-015-0833-4

Landau, B., & Jackendoff, R. (1993). Whence and whither in spatial language and spatial cognition? *Behavioral and Brain Sciences*, *16*(2), 255–265. https://doi.org/10.1017/S0140525X00029927

Logan, G. D. (1995). Linguistic and conceptual control of visual spatial attention. *Cognitive Psychology*, *28*(2), 103–174. https://doi.org/10.1006/cogp.1995.1004

Lovett, A., & Franconeri, S. L. (2017). Topological relations between objects are categorically coded. *Psychological Science*, *28*(10), 1408–1418. https://doi.org/10.1177/0956797617709814

McCormick, P. A., & Jolicoeur, P. (1992). Capturing visual attention and the curve tracing operation. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(1), 72–89. https://doi.org/10.1037/0096-1523.18.1.72

Miller, G. A., & Johnson-Laird, P. N. (1976). *Language and perception*. Cambridge University Press, Harvard University Press.

Nah, J. C., & Geng, J. J. (2022). Thematic object pairs produce stronger and faster grouping than taxonomic pairs. *Journal of Experimental Psychology: Human Perception and Performance*, *48*(12), 1325–1335. https://doi.org/10.1037/xhp0001031

O'Donnell, R. E., Clement, A., & Brockmole, J. R. (2018). Semantic and functional relationships among objects increase the capacity of visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *44*(7), 1151–1158. https://doi.org/10.1037/xlm0000508

Oliva, A., & Torralba, A. (2007). The role of context in object recognition. *Trends in Cognitive Sciences*, *11*(12), 520–527. https://doi.org/10.1016/j.tics.2007.09.009

Paparella, I., & Papeo, L. (2022). Chunking by social relationship in working memory. *Visual Cognition*, *30*(5), 354–370. https://doi.org/10.1080/13506285.2022.2064950

Papeo, L. (2020). Twos in human visual perception. *Cortex*, *132*, 473–478. https://doi.org/10.1016/j.cortex.2020.06.005

Papeo, L., & Abassi, E. (2019). Seeing social events: The visual specialization for dyadic human–human interactions. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(7), 877–888. https://doi.org/10.1037/xhp0000646

Papeo, L., Goupil, N., & Soto-Faraco, S. (2019). Visual search for people among people. *Psychological Science*, *30*(10), 1483–1496. https://doi.org/10.1177/0956797619867295

Papeo, L., Lingnau, A., Agosta, S., Pascual-Leone, A., Battelli, L., & Caramazza, A. (2015). The origin of word-related motor activity. *Cerebral Cortex*, *25*(6), 1668–1675. https://doi.org/10.1093/cercor/bht423

Papeo, L., Rumiati, R. I., Cecchetto, C., & Tomasino, B. (2012). On-line changing of thinking about words: The effect of cognitive context on neural responses to verb reading. *Journal of Cognitive Neuroscience*, *24*(12), 2348–2362. https://doi.org/10.1162/jocn_a_00291

Papeo, L., Stein, T., & Soto-Faraco, S. (2017). The two-body inversion effect. *Psychological Science*, *28*(3), 369–379. https://doi.org/10.1177/0956797616685769

Papeo, L., Vettori, S., Serraille, E., Odin, C., Rostami, F., & Hochmann, J. R. (2024). Abstract thematic roles in infants' representation of social events. *Current Biology*, *34*(18), 4294–4300.e4. https://doi.org/10.1016/j.cub.2024.07.081

Peelen, M. V., Berlot, E., & de Lange, F. P. (2024). Predictive processing of scenes and objects. *Nature Reviews Psychology*, *3*(1), 13–26. https://doi.org/10.1038/s44159-023-00254-0

Pylyshyn, Z. W. (2007). *Things and places: How the mind connects with the world*. MIT Press.

Quilty-Dunn, J. (2020). Concepts and predication from perception to cognition. *Philosophical Issues*, *30*(1), 273–292. https://doi.org/10.1111/phis.12185

Quilty-Dunn, J., Porot, N., & Mandelbaum, E. (2023). The best game in town: The reemergence of the language-of-thought hypothesis across the cognitive sciences. *Behavioral and Brain Sciences*, *46*, Article e261. https://doi.org/10.1017/S0140525X22002849

Riddoch, M. J., Pippard, B., Booth, L., Rickell, J., Summers, J., Brownson, A., & Humphreys, G. W. (2011). Effects of action relations on the configural coding between objects. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(2), 580–587. https://doi.org/10.1037/a0020745

Roberts, K. L., & Humphreys, G. W. (2010). The one that does, leads: Action relations influence the perceived temporal order of graspable objects. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(3), 776–780. https://doi.org/10.1037/a0018739

Roth, J. C., & Franconeri, S. L. (2012). Asymmetric coding of categorical spatial relations in both language and vision. *Frontiers in Psychology*, *3*, Article 464. https://doi.org/10.3389/fpsyg.2012.00464

Scholl, B. J., & Gao, T. (2013). Perceiving animacy and intentionality: Visual processing or higher-level judgment? In M. D. Rutherford & V. A. Kuhlmeier (Eds.), *Social perception: Detection and interpretation of animacy, agency, and intention* (Vol. 4629, pp. 197–230). Boston Review. https://doi.org/10.7551/mitpress/9780262019279.003.0009

Scholl, B. J., & Tremoulet, P. D. (2000). Perceptual causality and animacy. *Trends in Cognitive Sciences*, *4*(8), 299–309. https://doi.org/10.1016/S1364-6613(00)01506-0

Talmy, L. (1985). Lexicalization patterns: Semantic structure in lexical forms. In T. Shopen, (Ed.), *Language typology and syntactic description volume III: Grammatical categories and the lexicon* (pp. 57–149). Cambridge University Press.

Trueswell, J. C., Kaufman, D., Hafri, A., & Lidz, J. (2012). *Development of parsing abilities interacts with grammar learning: Evidence from Tagalog and Kannada*. Proceedings of the 36th annual Boston University conference on language development (pp. 620–632). Cascadilla Press.

Tye, M. (1997). *Ten problems of consciousness: A representational theory of the phenomenal mind*. MIT Press.

Ullman, S. (1984). Visual routines. *Cognition*, *18*(1-3), 97–159. https://doi.org/10.1016/0010-0277(84)90023-4

Vestner, T., Tipper, S. P., Hartley, T., Over, H., & Rueschemeyer, S. A. (2019). Bound together: Social binding leads to faster processing, spatial distortion, and enhanced memory of interacting partners. *Journal of Experimental Psychology: General*, *148*(7), 1251–1268. https://doi.org/10.1037/xge0000545

Vettori, S., Odin, C., Hochmann, J. R., & Papeo, L. (2024). A perceptual cue-based mechanism for automatic assignment of thematic agent and patient roles. *Journal of Experimental Psychology: General*. Advance online publication. https://doi.org/10.1037/xge0001657

Wong, K. W., & Scholl, B. J. (2024). Spontaneous path tracing in task-irrelevant mazes: Spatial affordances trigger dynamic visual routines. *Journal of Experimental Psychology: General*, *153*(9), 2230–2238. https://doi.org/10.1037/xge0001618

Wurm, M. F., Caramazza, A., & Lingnau, A. (2017). Action categories in lateral occipitotemporal cortex are organized along sociality and transitivity. *The Journal of Neuroscience*, *37*(3), 562–575. https://doi.org/10.1523/JNEUROSCI.1717-16.2016

Xu, S., Humphreys, G. W., & Heinke, D. (2015). Implied actions between paired objects lead to affordance selection by inhibition. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(4), 1021–1036. https://doi.org/10.1037/xhp0000059

Xu, Z., Chen, H., & Wang, Y. (2023). Invisible social grouping facilitates the recognition of individual faces. *Consciousness and Cognition*, *113*, Article 103556. https://doi.org/10.1016/j.concog.2023.103556

Yin, J., Csibra, G., & Tatone, D. (2022). Structural asymmetries in the representation of giving and taking events. *Cognition*, *229*, Article 105248. https://doi.org/10.1016/j.cognition.2022.105248

Yoon, E. Y., Humphreys, G. W., & Riddoch, M. J. (2010). The paired-object affordance effect. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(4), 812–824. https://doi.org/10.1037/a0017175

Yuan, L., Uttal, D., & Franconeri, S. (2016). Are categorical spatial relations encoded by shifting visual attention between objects? *PLOS ONE*, *11*(10), Article e0163141. https://doi.org/10.1371/journal.pone.0163141

Zanon, M., Lemaire, B. S., Papeo, L., & Vallortigara, G. (2024). Innate sensitivity to face-to-face biological motion. *Iscience*, *27*(2), Article 108793. https://doi.org/10.1016/j.isci.2024.108793

Received September 6, 2024
Revision received January 13, 2025
Accepted January 13, 2025 ■