



**HAL**  
open science

# The mental representation of quantitative dimensions: Origins and developmental course

Maria Dolores de Hevia

► **To cite this version:**

Maria Dolores de Hevia. The mental representation of quantitative dimensions: Origins and developmental course. Psychology. Université Paris Cité, 2023. tel-04699792

**HAL Id: tel-04699792**

**<https://hal.science/tel-04699792v1>**

Submitted on 17 Sep 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# *Apogée*

**Université Paris Cité**

Edition d'attestations de réussite

Demandeur: ROBERTM

Marlène ROBERT

# UNIVERSITÉ PARIS CITÉ

## ATTESTATION DE REUSSITE AU DIPLOME

La Présidente atteste que

**l' Habilitation à Diriger des Recherches SCIENCES FONDAMENTALES ET BIOMEDICALES**  
a été décernée à

**Madame MARIA DOLORES DE HEVIA ABUIN**  
née le 9 octobre 1976 à MADRID (ESPAGNE)

au titre de l'année universitaire 2022/2023

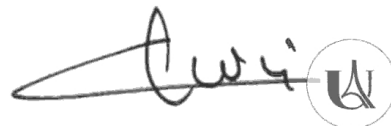
---

Date de soutenance : 16 février 2023

Etablissement soutenance : Université Paris Cité (UP Cité)

Jury : Mme JUDIT GERVAIN, Présidente du jury, DIRECTEUR DE RECHERCHE  
CNRS  
M. ARNAUD BADETS, Rapporteur du jury, CHARGE DE RECHERCHE HDR  
CNRS  
Mme JENNIFER COULL, Rapporteur du jury, CHARGE DE RECHERCHE HDR  
CNRS  
M. KONSTANTINOS PRIFTIS, Membre du jury, PROFESSEUR  
UNIVERSITE DE PADOUE  
Mme CATHERINE THEVENOT, Membre du jury, PROFESSEUR  
UNIVERSITE DE LAUSANNE

Fait à Paris, le 20 février 2023



Christine CLERICI

N° étudiant : 22227033

Document de synthèse  
soumis en vue de l'obtention d'une HDR

# The mental representation of quantitative dimensions: Origins and developmental course

Maria Dolores DE HEVIA ABUIN

Chargée de Recherche Classe Normale, CNRS

Integrative Neuroscience and Cognition Center, UMR 8002

# HDR Dossier

Maria Dolores DE HEVIA ABUIN

Integrative Neuroscience and Cognition Center  
UMR 8002  
Université de Paris - CNRS  
[deheviaolola@gmail.com](mailto:deheviaolola@gmail.com)

1. Curriculum vitæ
2. Publication list
3. PhD Diploma
4. Synthesis of Research Activity
5. Five main activities as a PI
6. Capacity to lead research
7. Research Projects

References

Annex 1: Journals rankings

# 1. Curriculum vitæ

Maria Dolores (Lola) de Hevia

Nationality, Spanish

Born in Madrid, Spain, 1976

One daughter (Boston, USA, July 2009), and one son (Paris, France, December 2018)

## Education

- 2004            PhD in Psychology, Universidad Complutense de Madrid (UCM), Spain.  
*Magna Cum Laude*. European PhD: Spain and Italy.
- 2000            Master in Organizational Psychology, UCM, Spain.
- 1999            Degree in Psychology (5-year program with expertise in Cognitive Science). UCM, Spain.

## Academic Appointments

- 2015            CNRS Research Scientist (CRCN). Integrative Neuroscience and Cognition Center (INCC, UMR 8002); previously Laboratoire Psychologie de la Perception (LPP, UMR 8242), Paris, France.
- 2012            Postdoctoral Fellow, NeuroSpin, Saclay, France, and LPP, Paris, France.
- 2011            Postdoctoral Fellow, LPP, University Paris Descartes, Paris, France.
- 2010            Research Associate (affiliate), Department of Psychology, Harvard University, USA.
- 2008            Postdoctoral Fellow, Mind, Brain and Behavior Initiative, Harvard University, USA.
- 2006            Fulbright Postdoctoral Fellow, Harvard University, USA.
- 2005            Postdoctoral Fellow, Università degli Studi di Milano-Bicocca, Italy.

## Research

Numerical processing; quantity and ordinal processing; links between number and space; use of space to represent non-spatial dimensions; newborns, infants, children and adults; behavioral and neuroimaging techniques.

## Bursary and Research fellowship

- 2012-2014      Marie Curie Postdoctoral Fellowship awarded by the European Union. NeuroSpin, INSERM, France, and LPP, CNRS, France. P.I.: Maria Dolores de Hevia.
- 2011-2012      Postdoctoral fellow funded by the European Research Council. P. I.: Veronique Izard. CNRS and University Paris-Descartes. France.
- 2010            Two-month research contract funded by the Italian Ministry of Research and Education. P.I.: Prof. Viola Macchi Cassia. Department of Psychology, University of Milano-Bicocca. Italy.

- 2008-2009 Postdoctoral Fellowship awarded by 'Mind, Brain and Behavior' Interfaculty Initiative at Harvard University. Faculty sponsors: Prof. Gennaro Chierchia, Department of Linguistics and Prof. Elizabeth Spelke, Department of Psychology. USA.
- 2007-2008 Postdoctoral Fellowship awarded by the Spanish Ministry of Education. Department of Psychology, Harvard University. USA.
- 2007 Postdoctoral Fellow at the Laboratory for Developmental Studies. Faculty: Prof. Elizabeth Spelke. Department of Psychology, Harvard University, USA.
- 2006-2007 Fulbright Postdoctoral Fellowship awarded by the Spanish Ministry of Education. Faculty contact: Prof. Elizabeth Spelke. Department of Psychology, Harvard University. USA.
- 2004-2005 Research Fellowship. P.I.: Prof. Giuseppe Vallar. Department of Psychology, University of Milano-Bicocca. Italy.
- 2003 Research contract funded by the Italian Ministry of Research and Education. P.I.: Prof. Giuseppe Vallar. Department of Psychology, University of Milano-Bicocca. Italy.
- 2002-2003 Scholarship awarded by the Italian Ministry of Foreign Affairs. Supervisors: Prof. Giuseppe Vallar and Prof. Luisa Girelli. Department of Psychology, University of Milano-Bicocca. Italy.
- 2001 Scholarship awarded by the Spanish Ministry of Foreign Affairs. Civil Hospital of Guadalajara, and Department of Psychology, University of Guadalajara. Mexico.
- 2001 Research training period. Supervisor: Prof. María Jesús Benedet Álvarez. Department of Psychology, Universidad Complutense de Madrid. Spain.

## Grants and Awards

- 2021 Thomas Jefferson Foundation (France-USA), 20.000\$. Project: The origins and development of the mental timeline. P.I. France: Maria Dolores de Hevia (Universite de Paris), P.I. USA: Ariel Starr (University of Washington).
- 2019 ANR PRC, Agence Nationale de la Recherche, France, 433.518 €. Project: How Domain-general Functions Contribute to the Development of Numerical Competencies. P.I.(coordinator): Andre Knops; co-P.I. (partner): Maria Dolores de Hevia.
- 2019 ANR PRC, Agence Nationale de la Recherche, France, 179.047 €. Project: Numbers in Action: Origins and Developmental Course. P.I.(coordinator): Maria Dolores de Hevia.
- 2016 ANR JC/JC, Agence Nationale de la Recherche, France, 109.304 €. Project: The Realm of Magnitude Representations: Origins and Neural Basis. P.I.(coordinator): Maria Dolores de Hevia.
- 2015 Fyssen Foundation, 21.500 €. Project: The Realm of Magnitude Representations: Origins and Neural Basis. P.I.: Maria Dolores de Hevia.
- 2012 Marie Curie Intra-European Fellowship for Career Development, FP7 EU, 265.000 €. Project: Uncovering the spatial nature of numbers: An investigation of its origins and neural basis. P.I.: Maria Dolores de Hevia.
- 2008 Jacobs Foundation, \$20.500. Project: Understanding numbers: Exploring the relation between numerical and spatial representations. P.I.: Maria Dolores de Hevia.
- 2007 Postdoctoral fellowship, Spanish Ministry of Education (MEC), \$37.000. One-year renewal of project funded by Fulbright-MEC fellowship. P.I.: Maria Dolores de Hevia.
- 2007 'Mind, Brain and Behavior' Initiative at Harvard University, Postdoctoral fellowship, \$50.000 (postponed to 2008).

- 2006 Fulbright-MEC Postdoctoral Fellowship, \$36.830. Project: Interactions between number processing and spatial representations: Emergence and developmental course. P.I.: Maria Dolores de Hevia.
- 2006 Postdoctoral fellowship, University of Milano-Bicocca, 37.500 € (deferred).
- 2004 Research project, University of Milano-Bicocca, 18.600 €.
- 2002 Foreign Students Award, Italian Ministry of Foreign Affairs, 6.000 €.
- 2001 Graduate Students Award, Spanish Ministry of Foreign Affairs, 4.000 €.

## Organizational Service

2015-2018. Co-organization (with Pia Rama) of weekly departmental seminars in the Laboratoire Psychologie de la Perception (LPP, CNRS UMR 8242; <http://lpp.parisdescartes.cnrs.fr/events/>).

2019-2021. Co-organization (with Cendra Agulhon and Claude Meunier) of weekly departmental seminars at the Integrative Neuroscience and Cognition Center (INCC, CNRS UMR 8002; <https://incc-paris.fr/events-and-news/>).

## Editorial service and Reviewer

*Ad-hoc reviewer for:*

Acta Psychologica;  
 Advances in Cognitive Psychology;  
 Annals of the New York Academy of Sciences;  
 Attention, Perception & Psychophysics;  
 Brain and Cognition;  
 British Journal of Psychology;  
 Child Development Perspectives;  
 Cognition;  
 Cognitive Development;  
 Cognitive Psychology;  
 Current Biology;  
 Developmental Science;  
 Developmental Medicine & Child Neurology;  
 Developmental Psychology;  
 Experimental Brain Research;  
 The European Journal of Developmental Psychology;  
 Frontiers in Behavioral Neuroscience;  
 Frontiers in Human Neuroscience;  
 Frontiers in Psychology;  
 Frontiers in Cognition;  
 Infancy;  
 Journal of Cognition and Development;  
 Journal of Cognitive Psychology;  
 Journal of Comparative Psychology;  
 Journal of Cross Cultural Psychology;  
 Journal of Experimental Psychology: General;  
 Journal of Experimental Child Psychology;  
 Learning and Individual Differences;



Neurophotonics;  
Neuropsychologia;  
Neuropsychology;  
Neuroscience & Biobehavioral Reviews;  
Perception;  
PLoS One;  
Psychonomic Bulletin & Review;  
Psychological Research;  
Quarterly Journal of Experimental Psychology;  
Royal Society Open Science;  
Scientific Reports;  
The Spanish Journal of Psychology;  
Timing & Time Perception.

#### *Funding Agencies:*

USA National Science Foundation (NSF)  
European Research Council (ERC)  
Luxembourg National Research Fund (FNR)

#### Evaluation committees:

##### *Master thesis:*

M2 2017 (Vicky Bouche)  
M2 2017 (Lea Combette)  
M1 2018 (Yumisay Rukoz)

##### *PhD thesis:*

Benoit Martin (NeuroSpin, 2017)  
Vanessa Andre (Universite de Rennes, 2017)  
Alessandra Pressigout (Université Paris Descartes, 2019)

## Media Coverage

*A little to the left, a lot to the right.* By Harvey Leifert, Natural History Magazine, March 2018.

<http://www.naturalhistorymag.com/samplings/043438/a-little-to-the-left-a-lot-to-the-right>

*L'effet SNARC chez les nouveau-nés?* Press communication CNRS and University Paris-Descartes, January, 29, 2018. <http://www.cnrs.fr/insb/recherche/parutions/articles2018/l-dehevia.html>

*Human Babies Have a Sense of Numbers From Birth.* By Surangya Kaur, NewsClick, Dec. 13, 2017.

<https://www.newsclick.in/human-babies-have-sense-numbers-birth>

*New study confirms newborns are supersmart.* By Ashley Edwards Walker, The Bump, Dec. 13, 2017.

<https://www.thebump.com/news/babies-understand-numbers-study>

*New Research Says Babies Understand Numbers Hours After They're Born & Their Knowledge Is Surprising.* By Azure Hall, Romper, Dec. 11, 2017.

<https://www.romper.com/p/new-research-says-babies-understand-numbers-hours-after-theyre-born-their-knowledge-is-surprising-7526557>

*Newborn babies know their numbers.* By Michael Price, Science Magazine, Dec. 7, 2017.

<https://www.sciencemag.org/news/2017/12/newborn-babies-know-their-numbers>

- Les nouveau-nés, capables de faire le lien entre l'espace, le temps et les quantités.* By Stéphanie Letellier, Notre famille, April, 4, 2014.  
<https://www.enfant.com/votre-bebe-0-1an/0-3mois/les-nouveau-nes-capables-de-faire-le-lien-entre-l-espace-le-temps-et-les-quantites.html>
- Les nouveaux-nés favorables à Kant.* By François Jarraud, L'Expresso, Le café Pédagogique, March, 27, 2014. <http://www.cafepedagogique.net/LEXPRE/SSO/Pages/2014/03/27032014Article635315024403906538.aspx>
- À la Une: Les nouveaux-nés favorables à Kant.* By Jeanne-Claire Fumet, Le café Pédagogique, March, 25, 2014.  
[http://www.cafepedagogique.net/lemensuel/lenseignant/lettres/philosophie/Pages/2014/151\\_1.aspx](http://www.cafepedagogique.net/lemensuel/lenseignant/lettres/philosophie/Pages/2014/151_1.aspx)
- Les nourrissons possèdent à la naissance une représentation de l'espace, du temps et des quantités.* Santé Mentale, March 19, 2014.  
<http://www.santementale.fr/actualites/les-nourrissons-possedent-a-la-naissance-une-representation-de-l-espace-du-temps-et-des-quantites.html>
- Les nouveau-nés font le lien entre l'espace, le temps et les quantités.* By Maureen Delorme, Maminou, March, 19, 2014. <http://maminou-lemag.com/article/print/675>
- Insolite: les nouveaux nés font déjà le lien entre l'espace et le temps.* By Catherine Cordonnier, Top Santé, March, 19, 2014.  
<https://www.topsante.com/maman-et-enfant/bebe/sante-de-bebe/insolite-les-nouveaux-nes-font-deja-le-lien-entre-lespace-et-le-temps-55583>
- Les nouveau-nés font déjà le lien entre l'espace, le temps et les quantités.* By Pierre-Yves Clause, Press communication CNRS and University Paris-Descartes, March, 18, 2014.  
[http://www2.cnrs.fr/sites/communique/fichier/cp\\_heviastrieri\\_mars2014.pdf](http://www2.cnrs.fr/sites/communique/fichier/cp_heviastrieri_mars2014.pdf)  
<http://www2.cnrs.fr/presse/communique/3469.htm?debut=120>
- Les nouveau-nés font déjà le lien entre l'espace, le temps et les quantités.* Press communication INSERM, March, 18, 2014.  
<http://presse.inserm.fr/les-nouveau-nes-font-deja-le-lien-entre-lespace-le-temps-et-les-quantites/11823/>

## Main collaborations

- Giuseppe **Vallar**, Viola **Macchi Cassia**, Luisa **Girelli**, Hermann **Bulf**, and Elena **Nava** (University of Milano-Bicocca, Italy).  
 Elizabeth **Spelke** (Harvard University, US).  
 Koleen **McCrink** (Barnard College, US).  
 Arlette **Streri**, Veronique **Izard**, Arnaud **Viarouge**, Pia **Rama**, and Andre **Knops** (University of Paris, France).  
 Ariel **Starr** (University of Washington, US).  
 Rosa **Rugani** and Mariagrazia **Ranzini** (University of Padova, Italy).  
 Bahia **Guellai** (University of Nanterre, France).

## Languages

Spanish, Italian, English, French

## 2. Publication list

### Peer-Reviewed Publications

(h-index: 22; 2279 citations; google scholar profile: <https://scholar.google.com/citations?user=bHJ3o3cAAAAJ&hl=es>)

# denotes publication with student

- #48. Decarli, G., Veggiotti, L., & **de Hevia**, M.D. (in press). The link between number and action in human infants. *Scientific Reports*
47. Viarouge, A., & **de Hevia**, M.D. (under review). What activates a shared representation underlying number-location and number-size associations?
- #46. Bourgaux, L., **de Hevia**, M.D., & Charras, P. (accepted, pre-registered report). Spatio-numerical mapping in 3D: is horizontal mapping the best candidate? *Experimental Psychology*.
- #45. Martin, L., Marie, J., Brun, M., **de Hevia**, M.D., Streri, A., & Izard, V. (under review). Abstract Representations of Small Sets in Newborns. *Cognition*
44. Nava, E., **de Hevia**, M.D., Bulf, H., & Macchi Cassia, V. (2022). Signatures of functional visuospatial asymmetries in early infancy. *Journal of Experimental Child Psychology*, 215, 105326. [https://www.sciencedirect.com/science/article/abs/pii/S0022096521002447?dgcid=rss\\_sd\\_all](https://www.sciencedirect.com/science/article/abs/pii/S0022096521002447?dgcid=rss_sd_all)
- #43. Bulf, H., Capparini, C., Nava, E., **de Hevia**, M.D., & Macchi Cassia, V. (2022). Space modulates cross-domain transfer of abstract rules in infants. *Journal of Experimental Child Psychology*, 213, 105270. (Citations 3). [https://www.sciencedirect.com/science/article/abs/pii/S0022096521001880?dgcid=rss\\_sd\\_all](https://www.sciencedirect.com/science/article/abs/pii/S0022096521001880?dgcid=rss_sd_all)
42. Viarouge, A., & **de Hevia**, M.D. (2021). Can a single representational object account for different number-space mappings? *Frontiers in Human Neuroscience*, section *Cognitive Neuroscience*, 15:750964. <https://www.frontiersin.org/articles/10.3389/fnhum.2021.750964/full>
41. **de Hevia**, M.D. (2021). How the human mind grounds numerical quantities on space. *Child Development Perspectives*, 15, 44-50. (Citations 2). <https://psycnet.apa.org/record/2021-06397-001>
- #40. McCrink, K., Veggiotti, L., & **de Hevia**, M.D. (2020). A left visual advantage for quantity processing in neonates. *Annals of the New York Academy of Sciences*, 1477(1), 71-78. (Citations 2). <https://europepmc.org/article/pmc/pmc7572742>
- #39. **de Hevia**, M.D., Macchi Cassia, V.M., Veggiotti, L., & Netskou, M.E. (2020). Discrimination of ordinal relationships in temporal sequences by 4-month-old infants. *Cognition*, 195, 104091. (Citations 4). <https://hal.archives-ouvertes.fr/hal-02372264/document>
- #38. Bonn, C.D., Netskou, M.E., Streri, A., & **de Hevia**, M.D. (2019). The association of changes in brightness with changes in number/duration in human newborns. *PLOS One* 14(10): e0223192. (Citations 3). <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0223192>
- #37. Dunn, H., Bernstein, N., **de Hevia**, M.D., Macchi Cassia, V., Bulf, H., & McCrink, K. (2019). Operational Momentum for Magnitude Ordering in Preschool Children and Adults. *Journal of Experimental Child Psychology*, 179, 260-275. (Citations 2). <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6311425/>
- #36. Borghesani\*, V., **de Hevia**\*, M.D., Viarouge\*, A., Pinheiro-Chagas, P., Eger, E., & Piazza, M. (2019). Processing number and length in the parietal cortex: sharing resources, not a common code. *Cortex*, 114, 17-27. \*joint first authorship. (Citations 27). <https://hal.sorbonne-universite.fr/hal-02173572/document>

35. McCrink, K., & **de Hevia**, M.D. (2018). From innate spatial biases to enculturated spatial cognition: The case of spatial associations in number and other sequences. *Frontiers in Psychology-Developmental Psychology*, 9, 415. (Citations 16).  
<https://www.frontiersin.org/articles/10.3389/fpsyg.2018.00415/full>
- #34. **de Hevia**, M.D., Veggiotti, L., Streri, A., & Bonn, C. (2017). At birth humans associate “few” with left and “many” with right. *Current Biology*, 27, 3879–3884.e2. (I.F. 9.704) (Citations 58).  
[https://www.cell.com/current-biology/pdfExtended/S0960-9822\(17\)31469-0](https://www.cell.com/current-biology/pdfExtended/S0960-9822(17)31469-0)
33. Macchi Cassia, V.M., Bulf, H., McCrink, K., & **de Hevia**, M.D. (2017). Operational Momentum during ordering operations for Size and Number in 4-month-old Infants. *Journal of Numerical Cognition*, 3, 270-287. (I.F. ) (Citations 6). <https://jnc-old.psychopen.eu/article/view/67/html>
- #32. Bulf, H., **de Hevia**, M.D., Gariboldi, V., Macchi Cassia, V.M. (2017). Infants learn better from left to right: a directional bias in infants' sequence learning. *Scientific Reports*, 7. (I.F. 5.228) (Citations 27).  
[https://www.researchgate.net/publication/317300822\\_Infants\\_learn\\_better\\_from\\_left\\_to\\_right\\_A\\_directional\\_bias\\_in\\_infants'\\_sequence\\_learning](https://www.researchgate.net/publication/317300822_Infants_learn_better_from_left_to_right_A_directional_bias_in_infants'_sequence_learning)
- #31. **de Hevia**, M.D., Lee, Y.N., & Streri, A. (2017). The temporal dimensions in the first year of life. *Timing & Time Perception Reviews*, 5, 280-296. (I.F. ) (Citations 12).  
[https://www.researchgate.net/publication/321766952\\_The\\_Temporal\\_Dimensions\\_in\\_the\\_First\\_Year\\_of\\_Life#fullTextFileContent](https://www.researchgate.net/publication/321766952_The_Temporal_Dimensions_in_the_First_Year_of_Life#fullTextFileContent)
30. **de Hevia**, MD., Castaldi, E., Streri, A., Eger, E., & Izard, V. (2017). Perceiving numerosity from birth. *Behavioral and Brain Sciences*, 40. (I.F. 14.2) (Citations 14).  
<https://www.cambridge.org/core/journals/behavioral-and-brain-sciences/article/abs/perceiving-numerosity-from-birth/8159CEFE887A288412FE7A87D536BDC3>
- #29. **de Hevia**, M.D., Addabbo, M., Nava, E., Croci, E., Girelli, L., & Macchi-Cassia, V.M. (2017). Infants' detection of increasing numerical order comes before detection of decreasing number. *Cognition*, 158, 177-188. (I.F. 3.411) (Citations 17). <https://pubmed.ncbi.nlm.nih.gov/27835788/>
28. Rugani, R., & **de Hevia**, M.D. (2016). Number-space associations without language: Evidence from preverbal human infants and nonhuman animal species. *Psychonomic Bulletin & Review*, 1-18. (I.F. 2.921) (Citations 47). <https://link.springer.com/article/10.3758/s13423-016-1126-2>
27. Rugani, R., McCrink, K., **de Hevia**, M.D., Vallortigara, G., & Regolin, L. (2016). Ratio abstraction over discrete magnitudes by newly hatched domestic chicks (*Gallus gallus*). *Scientific Reports*, 6, 30114. (I.F. 5.228) (Citations 24).  
[https://www.researchgate.net/publication/305715194\\_Ratio\\_abstraction\\_over\\_discrete\\_magnitudes\\_by\\_newly\\_hatched\\_domestic\\_chicks\\_Gallus\\_gallus](https://www.researchgate.net/publication/305715194_Ratio_abstraction_over_discrete_magnitudes_by_newly_hatched_domestic_chicks_Gallus_gallus)
26. **de Hevia**, M.D. (2016). Core mathematical abilities in infants: number and much more. *Progress in Brain Research*, 227, 53-74. (I.F. 3.256) (Citations 11).  
<https://www.sciencedirect.com/science/article/abs/pii/S0079612316300401>
- #25. Borghesani\*, V., **de Hevia**\*, M.D., Viarouge\*, A., Pinheiro-Chagas, P., Eger, E., & Piazza, M. (2016). Comparing magnitudes across dimensions: a univariate and multivariate approach. *Pattern Recognition in Neuroimaging*, IEEE, 1-4. \*joint first authorship. (Citations 1).
- #24. Macchi Cassia, V.M., McCrink, K., **de Hevia**, M.D., Gariboldi, V., & Bulf, H. (2016). Operational momentum and size ordering in preverbal infants. *Psychological Research*, 80, 360-367. (I.F. 2.863) (Citations 13). <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5319925/>
23. Bulf, H., **de Hevia**, M.D., & Macchi Cassia, V.M. (2016). Small on the left, large on the right: Numbers orient preverbal infants' visual attention onto space. *Developmental Science*, 19, 394-401. (I.F. 4.278) (Citations 96). <https://pubmed.ncbi.nlm.nih.gov/26074348/>
- #22. Coubart, A., Streri, M.D., **de Hevia**, M.D., & Izard, V. (2015). Cross-modal discrimination of 2 vs. 4 objects across touch and vision in 5-month-old infants. *PLOS One*. 10(3): e0120868.

- doi:10.1371/journal.pone.0120868 (I.F. 3.534) (Citations 45).  
<https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0120868&type=printable>
21. Streri, A., & **de Hevia**, M.D. (2015). Manual lateralization in infancy. *Frontiers in Psychology*, 5, 1575. (I.F. 2.8) (Citations 5). <https://www.frontiersin.org/articles/10.3389/fpsyg.2014.01575/full>
- #20. Gariboldi, V., Bulf, H., **de Hevia**, M.D., & Macchi-Cassia, V.M. (2014). Ordinal judgments move attention along representational space in infancy: Evidence from the Operational Momentum. *Giornale Italiano di Psicologia*, 3, 611-622
19. Bulf, H., Macchi-Cassia, V.M., **de Hevia**, M.D. (2014). Are numbers, size and brightness equally efficient in orienting visual attention? Evidence from an eye-tracking study. *PLOS One*, 9, e99499. (I.F. 3.534) (Citations 36).  
<https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0099499>
- #18. **de Hevia**, M.D., Addabbo, M., Girelli, L., & Macchi-Cassia, V.M. (2014). Human infants' preference for increasing left-to-right oriented numerical sequences. *PLOS One*, 9(5), e96412. (I.F. 3.534) (Citations 122). <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0096412>
- #17. **de Hevia**, M.D., Izard, V., Coubart, A., Spelke, E.S., & Streri, A. (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences*, 11, 4809–4813. (IF: 9.809) (Citations 276). <https://www.pnas.org/content/111/13/4809>
16. **de Hevia**, M.D., & Spelke, E.S. (2013). Not all continuous dimensions map equally: Number-Brightness mapping in human infants. *PLOS One*, 8(11): e81241. (I.F. 3.534) (Citations 23). <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0081241>
15. Viarouge, A., & **de Hevia**, M.D. (2013). The role of numerical magnitude and order in the illusory perception of size and brightness. *Frontiers in Psychology-Cognition*, 4, 484. (IF: 2.8) (Citations 22). <https://www.frontiersin.org/articles/10.3389/fpsyg.2013.00484/full>
- #14. Streri, A., **de Hevia**, M.D., Izard, V., & Coubart, A. (2013). What do we know about neonatal cognition? *Behavioral Sciences*, 3, 154-169. (Citations 43).  
[https://pdfs.semanticscholar.org/a9d9/28312af073c36ec9176f3135c28163aecfcd.pdf?\\_ga=2.75757405.95533168.1641806651-1176242119.1639660408](https://pdfs.semanticscholar.org/a9d9/28312af073c36ec9176f3135c28163aecfcd.pdf?_ga=2.75757405.95533168.1641806651-1176242119.1639660408)
- #13. Chinello, A., **de Hevia**, M.D., Geraci, C., & Girelli, L. (2012). Finding the SNARC in signed numbers: Notational effects in accessing number representation. *Functional Neurology*, 27, 177-185. (IF: 1.518) (Citations 9).  
[https://www.researchgate.net/publication/235602957\\_Finding\\_the\\_spatial-numerical\\_association\\_of\\_response\\_codes\\_SNARC\\_in\\_signed\\_numbers\\_Notational\\_effects\\_in\\_accessing\\_number\\_representation#fullTextFileContent](https://www.researchgate.net/publication/235602957_Finding_the_spatial-numerical_association_of_response_codes_SNARC_in_signed_numbers_Notational_effects_in_accessing_number_representation#fullTextFileContent)
12. **de Hevia**, M.D., Girelli, L., & Macchi-Cassia, V. (2012). Minds without language represent number through space: Origins of the mental number line. *Frontiers in Psychology*, 3(466). (IF: 2.8) (Citations 74). <https://www.frontiersin.org/articles/10.3389/fpsyg.2012.00466/full>
- #11. Macchi-Cassia, V., Picozzi, M., Girelli, L., & **de Hevia**, M.D. (2012). Increasing magnitude counts more: Asymmetrical processing of ordinality in 4-month-old infants. *Cognition*, 124, 183-193. (IF: 3.411) (Citations 35).  
[https://www.academia.edu/51104918/Increasing\\_magnitude\\_counts\\_more\\_Asymmetrical\\_processing\\_of\\_ordinality\\_in\\_4\\_month\\_old\\_infants](https://www.academia.edu/51104918/Increasing_magnitude_counts_more_Asymmetrical_processing_of_ordinality_in_4_month_old_infants)
- #10. **de Hevia**, M.D., Vanderslice, M., & Spelke, E.S. (2012). Cross-dimensional mapping of number, length and brightness by preschool children. *PLOS One*, 7(4), e35530. (IF: 4.4) (Citations 38).  
<https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0035530>
9. **de Hevia**, M.D. (2011). "Sensitivity to number: Reply to Gebuis and Gevers". *Cognition*, 121, 253-255. (IF: 3.162) (Citations 23). <https://psycnet.apa.org/record/2011-22061-009>
- #8. Perrone, G., **de Hevia**, M.D., Bricolo, E., & Girelli, L. (2010). "Numbers can move our hands: A spatial representation effect in digits handwriting". *Experimental Brain Research*, 205, 479-487. (IF: 2.395) (Citations 17).

[https://www.academia.edu/51104933/Numbers\\_can\\_move\\_our\\_hands\\_a\\_spatial\\_representation\\_effect\\_in\\_digits\\_handwriting](https://www.academia.edu/51104933/Numbers_can_move_our_hands_a_spatial_representation_effect_in_digits_handwriting)

- #7. Picozzi, M., **de Hevia**, M.D., Girelli, L., & Macchi Cassia, V. (2010). "Seven-month-old infants detect ordinal numerical relationships within temporal sequences". *Journal of Experimental Child Psychology*, 107, 359-367. (IF: 3.122) (Citations 47). <https://pubmed.ncbi.nlm.nih.gov/20579661/>
6. **de Hevia**, M.D., & Spelke, E.S. (2010). "Number-space mapping in human infants". *Psychological Science*, 21, 653-660. (IF: 4.431) (Citations 284).  
<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3129621/>
- #5. Previtali, P., **de Hevia**, M.D., & Girelli, L. (2010). "Placing order in space: The SNARC effect in serial learning". *Experimental Brain Research*, 201, 599-605. (IF: 2.395) (Citations 111).  
[https://www.researchgate.net/publication/38066330\\_Placing\\_order\\_in\\_space\\_The\\_SNARC\\_effect\\_in\\_serial\\_learning](https://www.researchgate.net/publication/38066330_Placing_order_in_space_The_SNARC_effect_in_serial_learning)
4. **de Hevia**, M.D., & Spelke, E.S. (2009). "Spontaneous mapping of number and space in adults and young children". *Cognition*, 110, 198-207. (IF: 3.162) (Citations 246).  
<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2705970/>
3. **de Hevia**, M.D., Vallar, G., & Girelli, L. (2008). "Visualizing numbers in the mind's eye: The role of visuo-spatial processing in numerical abilities". *Neuroscience & Biobehavioral Reviews*, 32, 1361-1372. (IF: 8.650) (Citations 167).  
[https://www.researchgate.net/publication/5270962\\_Visualizing\\_numbers\\_in\\_the\\_mind%27s\\_eye\\_The\\_role\\_of\\_visuo-spatial\\_processes\\_in\\_numerical\\_abilities](https://www.researchgate.net/publication/5270962_Visualizing_numbers_in_the_mind%27s_eye_The_role_of_visuo-spatial_processes_in_numerical_abilities)
2. **de Hevia**, M.D., Girelli, L., Bricolo, E. & Vallar, G. (2008) "The representational space of magnitude: Illusions of length". *Quarterly Journal of Experimental Psychology*, 61, 1496-1514. (IF: 1.964) (Citations 120).  
<https://moh-it.pure.elsevier.com/en/publications/the-representational-space-of-numerical-magnitude-illusions-of-length>
1. **de Hevia**, M.D., Girelli, L., & Vallar, G. (2006) "Numbers and space: A cognitive illusion?" *Experimental Brain Research*, 168, 254-264. (IF: 2.395) (Citations 140).  
<https://psycnet.apa.org/record/2008-05162-024>

## Other Publications

- de Hevia**, M.D. (2019). La notion de magnitude à la naissance. Representing magnitudes at birth. *Annales de la Fondation Fyssen*, 32, pp. 54-63.

## Book Chapters

- de Hevia**, M.D. (2016). 'Link between numbers and spatial extent from birth to adulthood', in A. Henik (Eds), *Continuous issues in numerical cognition: How many or how much*. Elsevier. (Citations 2).  
<https://psycnet.apa.org/record/2016-26289-002>
- de Hevia**, M.D., Vallar, G., & Girelli, L. (2006). "Visuo-spatial components of numerical representation", in T. Vecchi and G. Bottini (Eds), *Imagery and Spatial Cognition: Methods, Models and Cognitive Assessment*. (pp.155-171), Amsterdam: John Benjamins. (Citations 9).  
<https://benjamins.com/catalog/aicr.66.13hev>

## Conferences/Talks

63. Decarli, G., & **de Hevia**, M.D. (September, 2022). ESCOP
62. **de Hevia**, M.D. (September, 2022). ESCOP
61. **de Hevia**, M.D. (June, 2022). Invited talk at Ghent University, Mathematical Cognition and Learning Society, Belgium.
60. Veggiotti, L., Decarli, G., & **de Hevia**, M.D. (January, 2022). The link between number and action in human infants. Poster presented at BCCCD, organized by the Cognitive Development Center at CEU, Budapest (online conference).
59. Decarli, G., & **de Hevia**, M.D. (January, 2022). Human infants' processing of action-magnitude couplings. Poster presented at BCCCD, organized by the Cognitive Development Center at CEU, Budapest (online conference).
58. Veggiotti, L., Decarli, G., & **de Hevia**, M.D. (October, 2021). Number-action mapping in human infants. Talk presented at The Mathematical Cognition and Learning Society (online conference).
57. Veggiotti, L., & **de Hevia**, M.D. (June, 2021). Human infants can learn and generalize number-action mappings. Poster presented at Development in MOTION (DevMoCon) (online conference).
56. **de Hevia**, M.D. (March, 2021). How we use space to think about number. Invited (virtual) conference at University of Valladolid (Spain).
55. Gervain, J., Abboub, N., & **de Hevia**, M.D. (July, 2020). The discrimination of numerosities by newborn infants: an fNIRS study. Talk at vICIS, virtual International Conference on Infant Studies.
54. **de Hevia**, M.D. (July, 2020). Relating number to space in infants' quantifying and ordering abilities. Invited speaker at ICIS, International Conference on Infant Studies, Glasgow, Scotland (canceled, COVID-19 pandemic).
53. **de Hevia**, M.D. (June, 2020). Accepted talk at the Symposium 'About time for number: Investigating connections between temporal and numerical cognition'. Mathematical Cognition and Learning Society Conference, Dublin, Ireland (canceled, COVID-19 pandemic).
52. McCrink, K., & **de Hevia**, M.D. (October, 2019). A left visual advantage in newborn infants when processing magnitudes. Poster presented at the Cognitive Development Society Biennial Conference, Louisville, US.
51. **de Hevia**, M.D. (July, 2019). Two ways humans relate number and space from birth. Invited speaker at the Workshop Series in Cognitive Science: The Mind's Spatialization in Humans and Non-humans, Nice, France.
50. Bulf, H., Nava, E., **de Hevia**, M.D., & Macchi Cassia, V.M. (June, 2018). A left-to-right directional bias in infants' rule learning of numerical sequences. International Society for Infant Studies, Philadelphia, US.
49. **de Hevia**, M.D. (April, 2018). Chair at the symposium 'Numerical Processing II'. 1st Mathematical Cognition and Learning Society Conference, Oxford, UK.
48. McCrink, K., Macchi Cassia, V.M., Bulf, H., & **de Hevia**, M.D. (April, 2018). Interactions of Space and Arithmetic: Operational Momentum in Preschool Children. 1st Mathematical Cognition and Learning Society Conference, Oxford, UK.
47. **de Hevia**, M.D. (March, 2018). Origins and developmental course of number-space associations. Talk at the Laboratoire Vision, Action, and Cognition. Institut de Psychologie, Université Paris-Descartes, Boulogne-Billancourt, France.
46. McCrink, K., Dunn, H., Bernstein, N., Macchi Cassia, V.M., Bulf, H., & **de Hevia**, M.D. (October, 2017). Interactions of Space and Arithmetic: Operational Momentum in Preschool Children. Talk at Cognitive Development Society Biennial Conference, Portland, US.

45. Abboub, N., Gervain, J., & **de Hevia**, M.D. (October, 2016). Representing number and time in the newborn brain. Poster presented at the Society for functional Near Infrared Spectroscopy, Paris, France.
44. Bulf, H., **de Hevia**, M.D., & Macchi Cassia, V.M. (September, 2016). Asimmetrie spaziali nell'apprendimento di sequenze visive nella prima infanzia. Talk at the XXIX Congresso nazionale della sezione di psicologia dello sviluppo e dell'educazione, Vicenza, Italy.
43. Borghesani, V.\*, **de Hevia**, M.D.\*, Viarouge, A.\*, Pinheiro Chagas, P., Eger, E., & Piazza, M. (June, 2016). Comparing magnitudes across dimensions: a univariate and multivariate approach. International Workshop on Pattern Recognition in Neuroimaging, Trento, Italy. \*joint first authorship.
42. Macchi-Cassia, V.M., Gariboldi, V., Bulf, H., **de Hevia**, M.D., & McCrink, K. (May, 2016). Operational momentum during ordinal operations in 4-month-old infants. International Society for Infant Studies, New Orleans, US.
41. Borghesani, V.\*, **de Hevia**, M.D.\*, Viarouge, A.\*, Pinheiro Chagas, P., Eger, E., & Piazza, M. (May, 2016). Few:Many = Short: Long? Coding Of Magnitude Across Different Quantitative Dimensions. CAOS conference, Rovereto, Italy. \*joint first authorship.
40. **de Hevia**, M.D. (November, 2015). Invited talk for the conference 'Space and Mathematics: What's the Connection?'. Funded by NSF's Spatial Intelligence and Learning Center. Chicago, USA.
40. Macchi Cassia, V., Bulf, H., & **de Hevia**, M.D. (September, 2015). Spatial orientation modulates infants' learning from visual sequences. Seminar series at the Department of Psychology, University of Milano-Bicocca, Milan, Italy.
39. Bulf, H., Gariboldi, V., **de Hevia**, M.D., & Macchi Cassia, V. (July, 2015). Asymmetrical space processing in 7-month-olds: Left-to-right orientation facilitates learning of abstract rules. Poster presented in European Congress of Psychology, Milan, Italy.
38. Bulf, H., Gariboldi, V., **de Hevia**, M.D., & Macchi Cassia, V. (June, 2015). Left-to-right oriented sequences improve abstract rule learning in 7-month-old infants. International Conference on Interdisciplinary Advances in Statistical Learning, San Sebastian, Spain.
37. Marie, J., Martin, L., Coubart, A., **de Hevia**, M.D., Streri, A., & Izard, V. (March, 2015). Newborn infants detect correspondences in the numerical structure of visual vs. auditory sets. Poster presented at the Society for Research in Child Development-Biennial Meeting, Philadelphia, USA.
36. Bulf, H., Gariboldi, V., **de Hevia**, M.D., & Macchi Cassia, V. (January, 2015). Left-to-right orientation facilitates learning of abstract rules in 7-month-old infants. Poster presented in Budapest CEU Conference on Cognitive Development, Hungary.
35. Macchi Cassia, V., Gariboldi, V., Bulf, H., **de Hevia**, M.D., & McCrink, K. (January, 2015). Operational momentum during the representation of ordinal relations in 4- and 12-month-old infants. Poster presented in Budapest CEU Conference on Cognitive Development, Hungary.
34. Bulf, H., **de Hevia**, M.D., & Macchi Cassia, V. (2015). Small on the left, large on the right: Evidence for a Posner-SNARC effect in preverbal infants. Poster presented in Budapest CEU Conference on Cognitive Development, Hungary.
33. Gariboldi, V., Bulf, H., **de Hevia**, M.D., McCrink, K., & Macchi Cassia, V. (2014). Operational momentum during the representation of ordinal relations in 4- and 12-month-old infants. Poster presented at the Workshop on Cognition and Evolution CogEVO. Center for Mind/Brain Sciences, University of Trento, Italy.
32. Bulf, H., **de Hevia**, M.D., & Macchi Cassia, V. (2014). Magnitude information and oriented spatial codes in human infants. Invited talk at the Symposium 'Embodiment of abstract concepts: what's special about space?', University of Milan-Bicocca, Italy.
31. Bulf, H., Macchi Cassia, V., & **de Hevia**, M.D. (2014). Do numbers orient visual attention in infants? Evidence from an eye-tracking study. Poster presented at the International Society for Infant Studies, June, Berlin, Germany.



30. Macchi Cassia, V., Gariboldi, V., Bulf, H., McCrink, K., & **de Hevia**, M.D. (2014). Operational momentum during magnitude ordering in 12-month-old infants. Poster presented at the International Society for Infant Studies, June, Berlin, Germany.
29. Marie, J., **de Hevia**, M.D., Coubart, A., Streri, A., & Izard, V. (2014). Newborn infants detect correspondences in the numerical structure of visual vs. auditory sets. Poster presented at the Budapest CEU Conference on Cognitive Development, Budapest, Hungary.
28. Addabbo, M., Quirito, S., Gariboldi, V., **de Hevia**, M.D., & Girelli, L. (2013). La discriminazione delle relazioni numeriche ordinali a 4 mesi di vita: nuove evidenze di un vantaggio per l'ordine crescente. Poster presented at the XXVI Congresso nazionale della sezione di psicologia dello sviluppo e dell'educazione, Milan, Italy.
27. **de Hevia**, M.D., Marie, J., Coubart, A., Streri, A., & Izard, V. (2013). One-to-one correspondence cues for small sets enhance infants' arithmetic abilities. Poster presented at the Society for Research in Child Development-Biennial Meeting, Seattle, USA.
26. **de Hevia**, M.D. (2013). What babies know about space, time, and number. Invited talk at the Colloquium: Interactions between space, time, and number: 20 years of research. Collège de France, Paris, France.  
<http://www.college-de-france.fr/video/dehaene/2012-2013/Francais/sem-dehaene-hevia-20130226.mp4>
25. **de Hevia**, M.D., & Spelke, E.S. (2012). Not all continuous dimensions map equally: Number-Brightness mapping in infants. Poster presented at the International Society for Infant Studies, June, Minneapolis, USA.
24. **de Hevia**, M.D., Vanderslice, M., & Spelke, E.S. (2011). Cross-dimensional mapping of number, length and brightness by preschool children. Paper presented at the Cognitive Development Society, October, Philadelphia, USA.
23. **de Hevia**, M.D. (2011). "Constructing a mental number line". Journée scientifique annuelle du GDR Neurosciences Cognitives du Développement. June, Paris, France.
22. **de Hevia**, M.D., & Macchi Cassia V. (2011). "Early precursors of a number line". Paper presented at the Symposium 'Interactions of Space, Number and Ordering in Infancy and Early Childhood'. Society for Research in Child Development-Biennial Meeting, April, Montreal, Canada.
21. Macchi Cassia, V., Girelli, L., **de Hevia**, M.D., & Picozzi, M. (2011). "Four-Month-Old Infants' Detection of Order: An Advantage for Increasing Non-Numerical Sequences". Poster presented at the Society for Research in Child Development-Biennial Meeting, April, Montreal, Canada.
20. Macchi Cassia, V., **de Hevia**, M.D., Picozzi, M., Rumi, G., Perego, V., & Girelli, L. (2010). "Increasing magnitude counts more: evidence from 4-month-old infants' detection of non-numerical ordinal sequences". Poster presented at British Psychological Association, Developmental Section Conference, September, London, UK.
19. **de Hevia**, M.D., Picozzi, M., Girelli, L., & Macchi Cassia, V. (2010). "Left-to-right oriented number line: Infants' use of space to represent number magnitude". Poster presented at the International Society for Infant Studies, March, Baltimore, USA.
18. Katz, R., **de Hevia**, M.D., Izard, V., Spelke, E.S. (2010). "High tones and high places: Infants' mapping across tonal and spatial dimensions". Poster presented at the International Society for Infant Studies, March, Baltimore, USA.
17. Picozzi, M., **de Hevia**, M.D., Girelli, L., & Macchi Cassia, V. (2009). "Are 4-month-olds able to discriminate non-numerical ordinal sequences?" Poster presented at the Workshop on Cognition and Evolution CogEVO. Center for Mind/Brain Sciences, June, University of Trento, Italy.
16. Picozzi, M., **de Hevia**, M.D., Girelli, L., & Macchi Cassia, V. (2009). "Seven-month-old infants' ability to detect ordinal numerical relationships within temporal and spatiotemporal sequences". Poster presented at the Workshop on Cognition and Evolution CogEVO. Center for Mind/Brain Sciences, June, University of Trento, Italy.

15. **de Hevia**, M.D., & Spelke, E.S. (2009). "The Spatial-Numerical Link in Adults, Children, and Infants". Paper presented at the Symposium 'The Nature of Abstract Thought: Uncovering the Origin of Similarities Among Representations of Space, Number, and Time'. Society for Research in Child Development-Biennial Meeting, April, Denver, USA.
14. Picozzi, M., **de Hevia**, M.D., Girelli, L., & Macchi Cassia, V. (2009). 'Are 4-Month-Olds Able to Discriminate Ordinal Sequences of Non-Numerical Quantities?' Poster presented at the Society for Research in Child Development-Biennial Meeting, April, Denver, USA.
13. **de Hevia**, M.D. (2008). "Links between representations of number and space in early childhood and infancy". Poster presented at the Jacobs Foundation Conference 'Early childhood development and later achievement', 2-4 April, Marbach Castle, Germany.
12. **de Hevia**, M.D., & Spelke, E.S. (2008). "Connections between number and space in infancy". Poster presented at the International Society for Infant Studies, Vancouver, Canada.
11. Chinello A., **de Hevia**, M. D., Geraci C., & Girelli, L. (2007). "Finding the SNARC in number signs: Notational effects in accessing number representation". Poster presented at the III NUMBRA Summer School "Numeracy and Brain development: progress and prospects", 15-22 September, Santorini, Greece.
10. Perrone, G., **de Hevia**, M.D., & Girelli, L. (2007). "The influence of numerical information on the representation of space". Congresso Nazionale della Sezione di Psicologia Sperimentale, September, Como, Italy.
9. Perrone, G., **de Hevia**, M.D., & Girelli, L. (2007). "Mapping numbers onto space: Further support for the cognitive illusion hypothesis". Conference of the European Society for Cognitive Psychology (ESCOP), August, Marseille, France.
8. Girelli, L., Previtali, P., & **de Hevia**, M.D. (2007). "Serial learning induces spatially-organized mental representation". Conference of the European Society for Cognitive Psychology (ESCOP), August, Marseille, France.
7. **de Hevia**, M.D., Spelke, E.S. (2007). "The spatial representation of magnitude in children: Effects of number in the perception of a line". Society for Research in Child Development-Biennial Meeting, March, Boston, USA.
6. Perrone, G., **de Hevia**, M.D., Bricolo, E., Girelli, L. (2006) "Spatial effects on the writing of Arabic numbers". Congresso Nazionale della Sezione di Psicologia Sperimentale, 13-16 September, Rovereto, Italy.
5. Perrone, G., **de Hevia**, M.D., Bricolo, E. & Girelli, L. (2005). "Physical and symbolic distances in the representational space: Evidence from scanning visual images". XV Conference of the European Society for Cognitive Psychology (ESCOP), Leiden, Holland.
4. **de Hevia**, M.D., Girelli, L., Bricolo, E., & Vallar, G. (2005). "The impact of the numerical magnitude in the representation of space". Poster presented at the First NUMBRA / ESCOP Summer School "Neuroscience of number processing", 3-10 July, Erice, Italy.
3. **de Hevia**, M.D. (2005). "The influence of numerical magnitude in the representation of space". Invited oral presentation at the First NUMBRA / ESCOP Summer School "Neuroscience of number processing", 3-10 July, Erice, Italy.
2. **de Hevia**, M.D., Girelli, L., Bricolo, E. & Vallar, G. (2005). "The impact of numbers in the representational space: Mis-estimations of length". Paper presented at the XII Annual Cognitive Neuroscience Society (CNS) Meeting, 10-12 April, New York, USA.
1. **de Hevia**, M.D., Girelli, L., & Vallar, G. (2003). "Cognitive illusion of length induced by number magnitude". Paper presented at the XIII Conference of the European Society for Cognitive Psychology (ESCOP), 17-20 September, Granada, Spain.

# 3. PhD Diploma

Certified copies of PhD Diploma and European PhD Diploma (Universidad Complutense de Madrid, Spain, 2004)



## 4. Synthesis of Research Activity

I am a research scientist in the *Language and Cognition* Team, headed by Thierry Nazzi, in the Integrative Neuroscience and Cognition Center (INCC, UMR 8002, Université de Paris and CNRS), directed by Florian Waszak.

In my research I aim at characterizing a specific aspect of numerical cognition, the exploitation of spatial resources, by investigating the origins, developmental course and functional meaning of this phenomenon. Although in my research I have studied the human mind at various developmental stages (adults, children, infants, and newborns), it is nowadays heavily centered on the study of early precursors of higher cognition by means of experiments of humans from birth through their first year of life.

### Brief Introduction

Space offers an intuitive, concrete medium through which we can reason about, express and represent other non-spatial concepts (Tversky, 2014). Past and future can be associated, respectively, to the back and front with respect to one's own spatial position; happy and energetic suggest a bigger and higher space than sad and tired, which usually denote small and low; a combination of spatial axes characterizes relations between individuals (e.g., tree of life, organigramme, genealogical tree). One outstanding case of this phenomenon is the role that spatial thinking plays in numerical processing and mathematics: consider, for instance, the Cartesian coordinates, or the real number line, where all real numbers correspond to points in a one-dimensional line. In the 19th century Galton (1880) proposed that number and space are intimately related in the mind with his description of individuals reporting automatic access to specific, stable spatial configurations when thinking about numbers. Later empirical observations led researchers to consider this phenomenon more than a metaphor and to reach cognitive models of numerical cognition, which consider that numerical quantities are mentally organized on a horizontal, spatially oriented continuum: the 'mental number line' (Dehaene, 1992; Restle, 1970).

The capacity to estimate numerical quantities, without using language or counting, is a universal ability in humans (Dehaene, 1992) supported by a cognitive system that is evolutionary ancient (Piantadosi & Cantlon, 2017), preverbal (Xu & Spelke, 2000), and functional at birth (Izard et al., 2009). The question I address in my research is whether the number system connects to a spatial system as a result of experience and learning or whether this association is fundamental and unlearned. Recently, I am extending this question to the link between the action system and information of magnitude, such as number. In my research I propose that number and space are intrinsically related, that this link is functional from birth, and privileged for number, and that spatializing information can boost learning and memory from early in development. To substantiate these claims, I study a series of properties that characterize this relationship. Building from my proposal that the model of the 'mental number line', with its mapping of numbers onto space, reflects two properties of numbers (the magnitude and the ordinality) that lead each to a different type of number-space mapping (de Hevia et al., 2006, 2008; de Hevia, Girelli, et al., 2012; de Hevia, 2021), I argue that these two mappings are unlearned and fully functional at birth (de Hevia, Izard, et al., 2014; de Hevia, Girelli, et al., 2014; de Hevia, Veggioni, et al., 2017; de Hevia & Spelke, 2010). Further work has provided evidence for the numerical specificity of these phenomena from birth and across development (Bonn et al., 2019; Bulf et al., 2014; de Hevia, Vandervliet, et al., 2012; de

Hevia & Spelke, 2013; Viarouge & de Hevia, 2013). Recent work aims at shedding light on the functional properties of the different number-space mappings, which I argue promote efficient magnitude processing and ordinal coding (Bulf et al., 2017).

Below I present a synthesis of my research activity, organized by themes.

### 4.1. Effects of number on space perception

The study of the interaction between numerical and spatial representations has been devoted almost exclusively to investigating the effects that spatial variables exert on numerical processing. The seminal work by Dehaene and colleagues (Dehaene et al., 1993) provided the first empirical evidence supporting the hypothesis of an oriented mental number line: in Western cultures, humans tend to associate small numbers to the left side of space and large numbers to the right side of space (this phenomenon is known as the SNARC -Spatial Numerical Association of Response Codes- effect). During the last decades, an increasing body of evidence has shown that when adults engage in numerical processing, and even when numbers are irrelevant to the task at hand, their performance in behavioral tasks such as numerical comparison, line bisection, or stimulus detection, exhibits spatially-related effects that are consistent with the hypothesis of a spontaneous mapping of numbers onto an oriented space (Fias, 1996; Fischer et al., 2003; Knops et al., 2009; Zorzi et al., 2002).

The experimental work during my PhD focused on the opposite relationship: do numbers influence spatial processing? In a series of experiments, in collaboration with Giuseppe Vallar and Luisa Girelli (University of Milano-Bicocca, Italy), we adapted the line bisection task in order to present irrelevant numerical information during visuo-spatial processing. In this methodology, participants are presented with one line flanked at each side by a number, and are instructed to set the midpoint of the line in a fast but accurate way. No instructions regarding the numbers are provided. We observed a systematic bias towards the larger number irrespective of its position in the line. Crucially, the size of the biases did not vary with the numerical distance (or ratio) between the two flanking numbers, and thus we interpreted this result as a ‘cognitive illusion’ whereby the side ipsilateral to the larger number is perceived ‘larger’ and/or the side ipsilateral to the smaller number is perceived ‘smaller’ (de Hevia et al., 2006) (in analogy to the optical illusions in the figures of Müller-Lyer and in the combined forms of the Opel-Kundt; see Fig. 1).

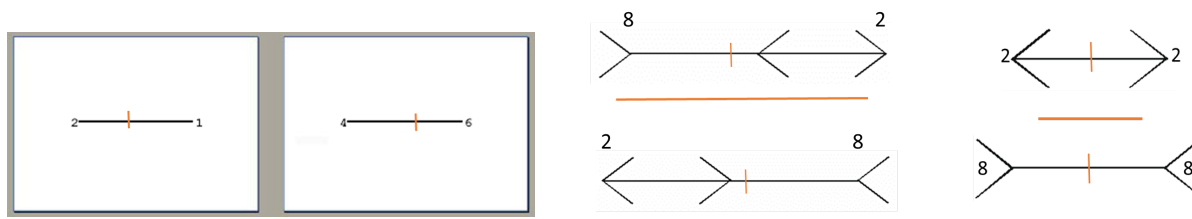


Figure 1. Left: Examples of line bisection stimuli flanked by numbers; adults systematically bisect the line towards the larger number (de Hevia et al., 2006). Right: the numerical bias is interpreted as a cognitive illusion of length, in analogy to the optical illusions: the colored segments represent the bisection bias, and the horizontal colored lines represent the spatial extent associated to the stimuli.

Further experiments tested the ‘cognitive illusion’ hypothesis through a computerized task. Participants are presented for 1 second with two numbers on the screen, separated by a variable

distance; afterwards, they are requested to manipulate a segment appearing on the screen in order to reproduce the length of the space between the two numbers, with no time limits. Results show that participants systematically underestimate the space delimited by two small numbers, while the same spaces are overestimated when they are delimited by two large numbers. Crucially, the absence of an effect of the numerical distance, or ratio, between the two numbers on the performance confirms previous observations with the line bisection paradigm, and provides support for the hypothesis of a 'cognitive illusion' brought about numerical size (de Hevia et al., 2008).

In an extension of this research, we tested the specificity of numerical information in bringing about this effect, by testing whether other types of ordinal information that do not convey magnitude information, as it is the case with the letters of the alphabet, might exert an influence in visuo-spatial representations. We also tested the presence of this effect using another quantitative, non-numerical dimension: the level of brightness of a figure. We found that numbers affect reproduction of spatial extent, replicating previous observations, but that they do not modulate reproduction of the level of brightness. Finally, we found that letters of the alphabet do not exert any influence in performance either, suggesting that ordinal information per se cannot bring about this spatial modulation (Viarouge & de Hevia, 2013).

We conducted other studies that capitalized on research, modeled after the classical Posner attention paradigm (Posner, 1980), showing that perceiving numbers causes spatial shifts of attention to the left or right sides of space, depending upon the numbers' magnitude (Fischer et al., 2003). In this work (Bulf et al., 2014), we investigated whether this phenomenon extends to non-symbolic numbers, as well as to the processing of the continuous dimensions of size and brightness, by exploring whether different dimensions are equally mapped onto space. After a numerical (i.e., symbolic Arabic digits or non-symbolic arrays of dots) or a non-numerical cue (i.e., shapes of different size or different brightness level) is presented, participants' saccadic response to a target that could appear at the left or the right sides of the screen was registered using an automated eye-tracker system. We have shown that, both in the case of Arabic digits and dot arrays, right targets are detected faster when preceded by large numbers, and left targets are detected faster when preceded by small numbers, than the reverse association. Moreover, participants are faster at detecting right targets when cued by large-sized shapes and left cues when cued by small-sized shapes, whereas brightness cues do not modulate the detection of peripheral targets. These findings indicate that looking at a symbolic or a non-symbolic number induces attentional shifts to a peripheral region of space that is congruent with the numbers' relative position on a mental number line, and that a similar shift in visual attention is induced by looking at shapes of different size.

Collectively, this work supports the idea that numbers correspond to different spatial lengths, varying parametrically with number magnitude (Restle, 1970). Moreover, irrelevant-to-the-task numbers can modulate visuo-spatial computations, and this effect critically depends on their information of magnitude. Numbers and brightness do not interact in this type of visuo-spatial tasks.

The findings from these experiments led us to hypothesize the existence of two number-space mappings. On the one hand, in the *number-spatial extent mapping*, numbers correspond to different spatial lengths/sizes, varying parametrically with number magnitude (Restle, 1970). This mapping accounts for the 'analogical' nature of numbers, and is commonly observed in the form of interactions between numerical and spatial (length, size, area) magnitudes, by virtue of all being continuous, quantitative dimensions. On the other hand, in the *number-spatial position mapping*, numbers correspond to different spatial positions, which are relative depending on the numerical range considered. This mapping accounts for the 'spatially oriented' nature of the number line, possibly appeals to both the

discrete and continuous nature of number, and is commonly observed in the form of associations between numerical magnitude and/or order and lateralized spatial positions, such as the SNARC effect (Dehaene et al., 1993). Therefore, we hypothesized that the mapping of numbers onto space is not only in the form of an oriented mental number line, but numerical representations also link to spatial representations in the form of a non-oriented mapping (i.e., number-spatial extent mapping).

## Effects of number on children's space perception

Following the studies previously reported on the effects of number on space perception, a natural question thus follows: where does this non-directional number-space mapping come from? One possibility is that exposure to mathematics education, which makes explicit the link between numbers and space through graphs, rulers and other measurement devices, is key to the development of this mapping. In fact, classical research on the development of this mapping has revealed that the SNARC effect is observable only after years of schooling, at 9 years of age (Berch et al., 1999).

During my postdoctoral stay at Harvard University, and in collaboration with Elizabeth Spelke, I conducted a series of experiments adapting the line bisection task to the evaluation of the effects of number on children's spatial processing. Previous research focusing on the number-space mapping during childhood had failed to disclose an early mapping. However, we reasoned that the number-spatial extent mapping would be observable in the childhood years earlier than previously thought. Critically, we employed non-symbolic numbers (arrays of dots) instead of the symbolic stimuli (Arabic digits), which researchers had employed until then. In fact, previous research had shown that children do not automatically access information of magnitude from the Arabic symbol until the age of 7 years (Girelli et al., 2000).

The first step was to ensure that adults' signature bias towards the larger Arabic number in the bisection of lines would extend to the bisection of lines flanked by non-symbolic numbers. We tested a group of adults with stimuli that included both lines flanked by Arabic numbers as well as lines flanked by arrays of dots. The results showed that the signature bias was present for both numerical formats and that, critically, the biases were similar in nature (no significant effects of stimulus notation were found). The next step was to test children. We started testing 7-year-old children with both types of stimuli: we found that a signature bias towards the larger number was found for lines flanked by non-symbolic number, while the phenomenon was absent for lines flanked by symbolic number. Therefore, we successfully disclosed the presence of a non-directional, number-spatial extent mapping in children younger than previously reported, and this finding was made possible through the use of non-symbolic instead of symbolic-number.

Finally, we presented the same task to 5-year-old children. Children at this age were only presented with lines flanked by non-symbolic number, since symbolic number did not produce any effects in 7-year-old children. As for adults and 7-year-old children, 5-year-old children were found to present a systematic bias towards the side ipsilateral to the larger non-symbolic number (see Fig. 2). Crucially, the analyses comparing this effect to the one present in adults and 7-year-old children were found to be similar (no effects of age range were found to be significant).

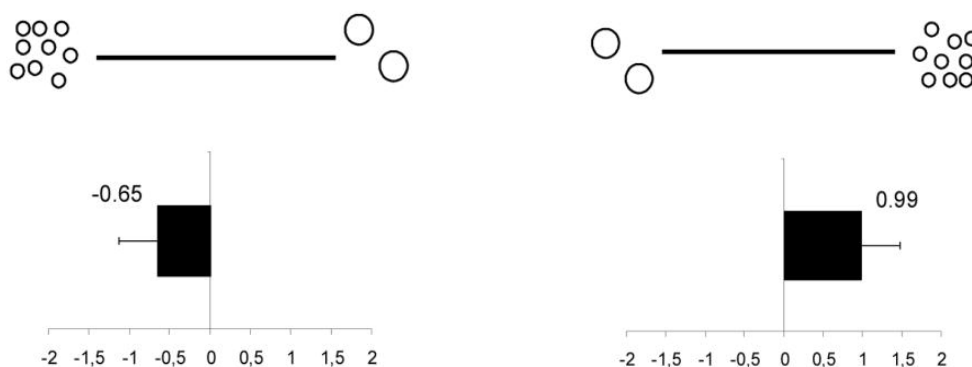


Figure 2. Mean values ( $\pm$ s.e.) of bisection performance (mm) for lines flanked by non-symbolic displays in 5-year-old children. A systematic, similar bias towards the larger numerosity was found across experiments using displays that controlled for non-numerical properties of the displays, such as the total area, total contour length, and distance between the line and the flankers.

An additional set of experiments were conducted in 5-year-old children in order to verify that this effect was not related to any non-numerical continuous dimension. The stimuli we employed for the non-symbolic condition with all our participants (adults, 7- and 5-year-old children) controlled for the overall area occupied by the single elements of the array. Two further experiments were run in order to control for the total contour length, the overall area occupied by the array configuration, and the space between the flanking array and the end of the line. In all these conditions, children systematically bisected the line towards the larger non-symbolic number, and the effect was similar across conditions (no effects of experimental condition were found to be significant).

This work constituted the first report on the (non-directional) number-spatial extent mapping in children as young as 5 years of age, and formed the basis for new research undertaken with even a younger population: preverbal human infants and humans at birth.

## 4.2. Mapping number and space in infancy and at birth

Following the studies on children's mapping of number and space (de Hevia & Spelke, 2009), and (by that time) recently published evidence that even uneducated adults spontaneously map number onto space (Dehaene et al., 2008), we hypothesized that our minds might be predisposed to treat number and space as intrinsically related (at least in the form of a number-spatial extent mapping).

Infants' numerical (Xu & Spelke, 2000) and spatial (Newcombe & Huttenlocher, 2003) capacities had been revealed to be the foundations of the numerical and spatial systems present in adulthood. However, how these systems of representation link during infancy had never been the focus of research at that time. I undertook this project in collaboration with Elizabeth Spelke, in order to shed light on the origins of the (non-oriented) number-spatial extent mapping.



By means of two different methods routinely used in developmental studies with human infants, we tested infants' numerical and spatial discrimination abilities, as well their abilities to relate both types of information. In a first experiment, we habituated 24 eight-month-old infants to a series of either increasing or decreasing numerosities, while measuring their looking times to the numerical displays that changed in magnitude following a 1:2 ratio (this ratio ensures successful discrimination at this age, Xu & Spelke, 2000). Once the looking time decreased significantly, signaling that habituation had been reached, we presented a series of line lengths that differed in magnitude following the same 1:2 ratio, alternating increasing and decreasing order trials. If infants spontaneously relate numerical and spatial information, then they should be able to transfer discrimination of the ordinal information embedded in the numerical series to the displays showing different line lengths. As a result, infants habituated to increasing number should look longer to the lines following a decreasing order, and infants habituated to the decreasing numerical order should look longer to the series of lines following an increasing order. In fact, that was the pattern of results that we obtained: infants generalized the habituation looking pattern (low looking times) to the series of lines that followed the familiar order, and looked significantly longer at the series of lines that followed the novel order at test (Fig. 3).

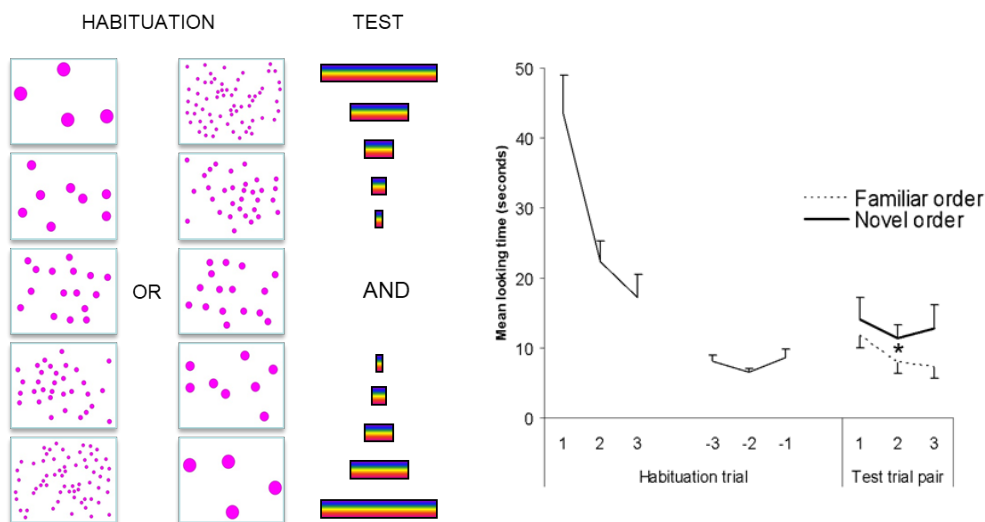


Figure 3. Left: Infants are habituated to either increasing or decreasing numerosities and are tested with both increasing and decreasing series of line lengths. Right: Infants habituate to the numerical sequences during the habituation phase and dishabituate to the new order in line length during the test trials. From de Hevia & Spelke (2010). Psychological Science.

A second series of experiments was aimed at extending this finding with a different method, testing whether infants at the same age would map number and space in absence of explicit ordinal cues. We employed a habituation paradigm, by presenting the information of number and space at the same time, but following no predictable order. A first group of 20 infants were presented with a rule that established a positive (congruent) relationship between number and space: the larger the number, the longer the line. When attention to these displays diminished significantly, we presented infants with two new test trials: in one trial new numbers and new lines were presented following the familiar (congruent) rule, and in a different trial new numbers and new lines were presented following a novel (incongruent) rule, where the larger the number, the shorter the line. We measured the looking times during the presentation of these test trials and found a significantly higher looking time at the test trial presenting the familiar (congruent) rule applied to new numbers and line lengths. Therefore, infants were able to learn

the rule 'the larger the number, the longer the line length associated', and apply it to new instances of numbers and line lengths.

While these results suggest that infants can learn a rule that establishes a positive, congruent relationship between number and space, it does not establish whether this link has a predefined direction (i.e., it has to be congruent), or whether infants would accept any given pairing between these two sources of information. Therefore, we tested a second group of 8-month-old infants with similar methods and materials, except that the rule shown during familiarization established a negative (incongruent) relationship between number and space: the larger the number, the shorter the line. Note that this rule is equally predictable as the positive, congruent one, except that the two dimensions are paired incongruently. During test trials, infants were presented with the same stimuli than the group familiarized with the positive, congruent rule. In contrast to those infants, however, in the incongruent rule condition infants did not show any preference for any of the two mappings at test, looking equally to the trials showing new numbers and line lengths paired either congruently or incongruently. This finding suggests that infants are not able to learn an incongruent rule between number and spatial length and therefore fail to apply it to new instances during the test trials.

This series of experiments show that infants at 8 months of age do spontaneously map number onto space, and that this mapping has a privileged direction: both sources of information must be positively aligned to each other.

## Mapping number and space (and time) at birth

As part of my postdoctoral work at the Laboratoire Psychologie Perception (LPP; now INCC), and in collaboration with Veronique Izard and Arlette Streri, we conducted a series of experiments addressing the following question: do infants have the ability to map number and space (and time) from birth? While it had been shown that from birth humans have the ability to discriminate numerical information in an abstract way (Izard et al., 2009), we did not know whether this representation establishes a spontaneous mapping with other dimensions from birth. We conducted a series of six experiments in the maternity ward of Hospital Bichat (Paris) that investigated whether human newborns are sensitive to, and create expectations of, congruent changes in magnitude across the dimensions of number, spatial and time (de Hevia, Izard, et al., 2014). The paradigm we employed had two phases: a familiarization phase (60 seconds) immediately followed by a test phase. All infants were presented with two values of numerosities and/or durations (one small and one large), and two values of length (one small and one large). This manipulation was critical as we needed newborns to form representations of relative magnitude for both number, spatial extent and temporal duration. During familiarization, one of the auditory stimuli (either 6 or 18) was paired with one visual length (either a small or large rectangle). Afterwards, during the test, the auditory numerosity and/or duration was changed (from small to large -from 6 to 18- or from large to small -from 18 to 6-), and this new auditory numerosity was paired with the familiar and the novel visual length in two successive trials. Compared to familiarization, test trials thus contained either one change (auditory change only, as the numerosity always changed but in one trial was paired with the familiar line length) or two changes (auditory and visual changes, when the new numerosity was paired with the new line length). Crucially, two familiarization conditions were created such that in the two-change trials the auditory numerosity/duration and visual length either changed in the same direction (either both increasing or both decreasing), or in opposite directions (one increasing, the other decreasing; see Fig. 4).

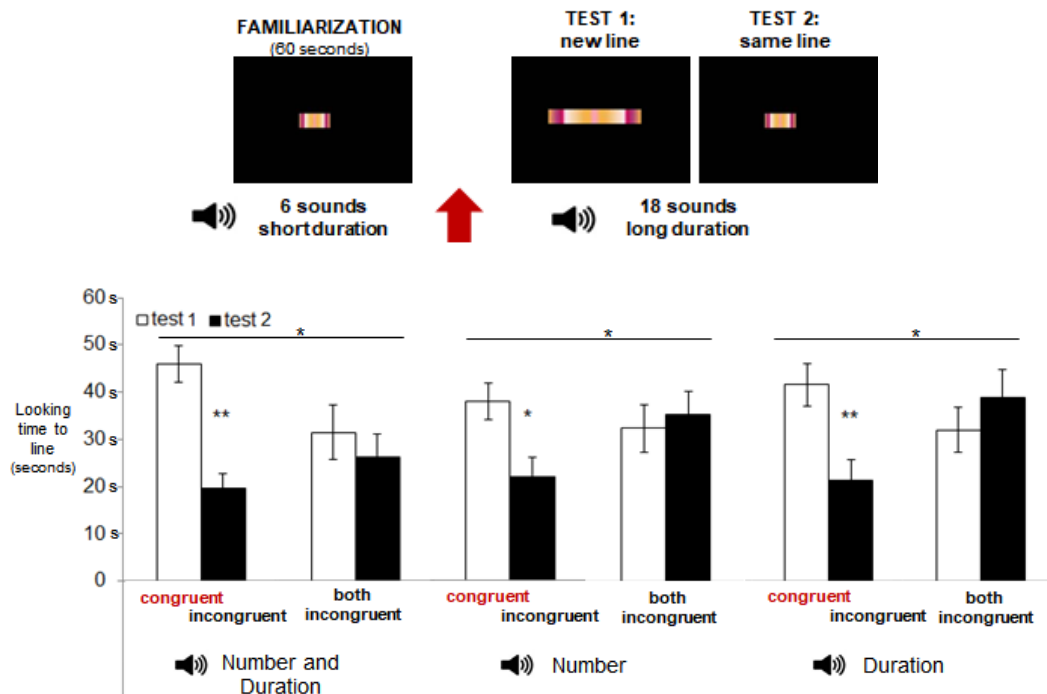


Figure 4. Top: Newborns are first familiarized to an auditory sequence of syllables of variable number, either 6 or 18 (6, in the example above), and are shown simultaneously a visual object of variable size, either small or large (small, in the example above). After 60 seconds of exposure to this bi-modal (i.e., auditory and visual) information, they experience a change in auditory number, either from 6 to 18 or from 18 to 6 (from 6 to 18, in the example above). This new auditory information is presented in two different test trials: in one test trial, the visual object is new with respect to the one observed during the familiarization phase (large object, in the example above); in a second test trial, the visual object is the same as in the familiarization phase (small object, in the example above). We measured the time newborns spent looking at these two test trials, and found that newborns systematically look longer to the object that corresponds to the new numerosity heard (i.e., small object if the new numerosity is 6, and large object if the new numerosity is 18). Bottom: Looking times to the two test trials across different conditions: conditions where number and duration are confounded in the auditory stimuli (Number and Duration); when only numerical information, but not duration, is present in the auditory sequences (Number); when only duration, but not numerical information, is present in the auditory sequences (Duration). For each of these conditions, we also tested newborns in equivalent changes in stimulation that did not contain corresponding changes in magnitude (e.g., we familiarized with 6 syllables and a large object, and during the test we changed the numerosity to 18, which was presented with the large and the small object; in this condition, newborns do not have the possibility to experience a corresponding change in spatial extent; in the graph these conditions correspond to the bars labeled 'both incongruent'). The order of test trials (first new object vs. second) varies equally across newborns, as well as the type of familiarization received (6 syllables accompanied by a small object vs. 18 syllables accompanied by a large object). Adapted from de Hevia, M.D., Izard, V., Coubar, A., Spelke, E.S., Streri, A., 2014. Representations of space, time and number in neonates. *Proc. Natl. Acad. Sci. U.S.A.* 111(13), 4809-4813.

To succeed in our tests, newborns have to build an expectation of congruency between magnitude-related changes in number and/or time, and space, from familiarization to test. Notably, neonates revealed this sensitivity both when numerical and temporal cues were simultaneously available, and when number and duration was presented in isolation. Taken together, these findings show that the

human mind thus may be predisposed to relate these three fundamental dimensions prior to any experience with the natural correlations between numbers of objects, visual spatial extents, and auditory temporal durations. They also show that these mappings are not the result of an association learnt through a statistical learning mechanism that can establish associations between any variables even if these are arbitrary and meaningless; on the contrary, newborns' performance indicates that the information of magnitude presented in the form of number (and/or duration) and spatial length has to be congruent at an abstract, magnitude level.

### 4.3. Specificity of the number-space mapping

Adults can form translations between any dimensions of magnitude (J. C. Stevens & Marks, 1965), however it is not clear whether humans at earlier stages of development are similarly flexible. Building on the finding that children, infants, and newborns are able to spontaneously map numerosities onto space (de Hevia, Izard, et al., 2014; de Hevia & Spelke, 2009, 2010), we asked whether this mapping reflects a general ability to map any continuous dimension onto any other, and therefore the number-spatial extent mapping would be an instance of a more general ability, or whether this mapping reflects a privileged connection between the domains of number (and time) and space.

We started addressing these questions through studies of cross-dimensional mappings with 4- to 5-year-old children (de Hevia, Vandervelde, et al., 2012). We asked children to first map the dimensions of number, line length, and level of brightness in a series of intra-dimensional mappings in order to verify that children would understand the task in the absence of explicit instructions. We presented children with cards depicting different non-symbolic numbers, different line lengths and different levels of brightness, and asked them to map one series of cards to a second series of cards. We verified that children performed significantly above chance for the intra-dimensional mappings of all the three dimensions. Next, we tested children in the crucial mappings: inter-dimensional mappings between these dimensions, where each dimension (number, length and brightness) is mapped onto each other. Thus, using the same materials and methods, we presented children with different blocks of inter-dimensional mappings: number-line length (the larger the number, the longer the line), line length-brightness (the longer the line, the brighter the object), and brightness-number (the brighter the object, the larger the number). We tested different groups of children, one group of children with a (positive) congruent mapping between each of these inter-dimensional mappings, a second group of children with (positive) congruent inter-dimensional mappings but with a different direction of the mapping (e.g., from number to length vs. from length to number), and a final group of children where they were asked to map the dimensions in a (negative) incongruent way (e.g., the larger the number, the shorter the line).

For the inter-dimensional mappings, we obtained different patterns of performance depending on the dimensions to be mapped. On the one hand, for the positive inter-dimensional mappings, only the number-length mappings (in both directions), and the length-brightness mappings (in one direction) were mapped significantly above chance; in contrast, the two positive inter-dimensional mappings of number-brightness were not performed above chance. On the other hand, for the negative inter-dimensional mappings, none of the mapping conditions were performed significantly above chance. These results suggest a series of conclusions. First, the number-length mappings might have a privileged status at the start of the school years, in line with the pervasive presence of these mappings in adulthood; second, the mappings of one magnitude dimension, such as number and brightness, onto the dimension of length are intuitive for these children, suggesting that space might function as a privileged dimension onto which other sources of information are intuitively mapped; third, not all the continuous dimensions map onto any other in the same way, at least at the age tested in this study.

Because the preliminary evidence from children suggesting that some dimensions are more easily associated than others could be accounted for by the fact that the number-spatial extent mapping is encountered more frequently in the natural environment as well as in formal education, we asked this question earlier in development with studies on infants. We used the same methods that in the past disclosed the presence of number-space mappings (de Hevia & Spelke, 2010). We tested, in collaboration with E. Spelke at Harvard University, 8-month-old infants in their ability to create mappings between number and the level of brightness (de Hevia & Spelke, 2013). In this study we obtained a pattern of performance both quantitatively and qualitatively different from infants' performance on the number-space mapping. First, when infants are presented with a series of numerical order (either increasing or decreasing), and are later tested with a series of different levels of brightness (both in increasing and in decreasing order), infants do not show any significant difference in their looking times during the test trials. Therefore, infants at this age do not appear to be able to transfer the discrimination from a series of numerical displays to a series of brightness levels. Second, when infants are presented explicitly with the positive mapping between number and brightness, using a method where the two dimensions are presented at the same time, they show a significantly different pattern of looking time during the test trials: they prefer to look at the new rule at test, showing evidence that they have extracted the rule during the habituation phase and applied it to new exemplars during test. Third, when the rule presented to infants shows the two dimensions mapped in an incongruent way, at test infants do not show any evidence of discriminating between the different trials, since their looking times do not differ significantly.

There are some similarities between infants' performance for the number-space and the number-brightness mappings: for both mappings, infants are able to extract the information of a rule establishing a positive relationship between the two dimensions and use it productively, so that they can recognize it in new exemplars following the same rule. However, in the number-space mappings infants prefer to continue looking at the new information that follows a congruent mapping (they look at the familiar, congruent mappings), whereas in the number-brightness mappings infants do not show this preference for the new, congruent mappings (they look at the novel, incongruent mappings). This finding suggests that the congruent number-space mappings might recruit attentional resources that drive infants to continue looking at them despite being familiar, whereas the congruent number-brightness mappings, even if they can be learnt, do not seem to have this impact on infants or recruit their attention.

## Specificity of the number-space mapping at birth

Based on our previous study showing that human neonates spontaneously associate changes in magnitude across the dimensions of number, length, and duration (de Hevia, Izard, et al., 2014), we asked whether these particular associations generalize to other pairs of magnitudes in the same way at birth, or whether they reflect an early predisposition to expect specific relations between spatial, temporal, and numerical representations.

In order to address this question, we tested mappings of number onto visual brightness and subsequently compared these with the previous study on number-length mappings. We tested forty-eight newborn infants assigned to three different conditions in which increasing or decreasing auditory numerosities were paired with visual objects that changed in luminance/contrast or shape (a non-magnitude control). In the Congruent condition, infants were familiarized to either a low-luminance stimulus paired with a small number of syllables or a high-luminance stimulus paired with a large number of syllables; in the Incongruent condition, infants were familiarized to either a low-luminance stimulus paired with a large number of syllables or a high-luminance stimulus paired with a small number of

syllables; and in order to control for visual novelty, a Shape-Change control condition, in which an object of one of two shapes rather than luminance values was paired with a small or large number of syllables. Following familiarization, infants experienced two test trials with a novel numerical stimulus; infants familiarized with a small number of syllables experienced a large number in the two test trials, while infants familiarized with a large number of syllables were tested with a small number. The crucial manipulation was in the type of visual change: during 1-Change test trials, no visual feature change accompanied the numerical change. During 2-Change trials, both the visual feature (brightness or shape) changed as well as the number of syllables heard.

Results indicated that newborns preferred magnitude-matched changes in brightness over no change in brightness. In contrast, infants showed no relative preference for a shape change over no shape change. When an increase in brightness accompanied a decrease in number (and vice versa), newborns showed an intermediate pattern of looking times indistinguishable from magnitude-matched changes in brightness or magnitude-neutral changes in shape. This performance pattern contrasts with the published number-length experiment, in which newborns strongly dispreferred magnitude-reversed changes in length accompanying auditory number.

These results suggest that newborns seem to treat parallel changes in brightness and number more flexibly than parallel changes in length and number. We interpret this result as support for the hypothesis that numerical, spatial, and temporal magnitudes are more strongly associated with each other at birth than with brightness.

Collectively, while these results show that children, infants, and newborns are able to establish mappings between different continuous dimensions, they suggest that different mappings might have a different status, with the number-spatial extent mapping being more easily established, and preferred, than other mappings. The findings indicate that at birth, and the first months of life, humans can map three pairs of extensive dimensions -number and space (de Hevia, Vandervel, et al., 2012; de Hevia, Izard, et al., 2014; de Hevia & Spelke, 2009, 2010), time and space (de Hevia, Izard, et al., 2014; Srinivasan & Carey, 2010), and number and time (de Hevia, Izard, et al., 2014)-, and one pair of intensive dimensions -brightness and loudness (Lewkowicz & Turkewitz, 1980)-, but fail to relate dimensions belonging to different categories -loudness and length (Srinivasan & Carey, 2010) or number and brightness (Bonn et al., 2019; de Hevia, Vandervel, et al., 2012; de Hevia & Spelke, 2013)-.

#### 4.4. A (directional) number-spatial position mapping

As previously argued, we hypothesize the existence of a (directional) number-spatial position mapping, in addition to the (non-directional) number-spatial extent mapping, which would be at the origins of the classical SNARC effect, the advantage to respond to small numbers with the left hand and to large numbers with the right hand (Dehaene et al., 1993).

The first series of experiments we conducted, in collaboration with Viola Macchi Cassia and Luisa Girelli (University of Milano-Bicocca, Italy), aimed at testing infants' ordinal abilities. We know from the adult literature that order information is highly relevant for the oriented spatial mapping: different numerical and non-numerical ordinal series have been found to be spatially oriented (Gevers et al., 2003, 2004). Therefore, an investigation of the origins of the spatial orientation of numbers might start from the study of infants' ability to discriminate ordinal information. However, in the developmental literature only a couple of studies had investigated this ability in infants, suggesting that the ability to extract ordinal

information embedded in a numerical series is available from the age of 11 months (Brannon, 2002). Our studies on the number-space mapping had revealed, however, that infants at the age of 8 months are already capable of using ordinal information for both numerical and non-numerical series. The crucial difference between our studies and the previous work was the use of different geometrical figures and colors to represent the numerical arrays. In fact, the use of featural (shape and color) information is known to boost infants' extraction of ordinal information (Kirkham et al., 2002). Thus, we tested 7-month-old infants' ability to extract ordinal numerical information. We used featural cues that would help extract the ordinal rule: a group of infants was habituated to increasing numerical sequences, the other group to decreasing numerical sequences, and during the test trials both groups were presented with both increasing and decreasing numerical sequences. Infants in both groups showed a significantly higher looking time to the series at test that followed the novel order, suggesting that infants at this age are able to extract the information of order embedded in a numerical series (Picozzi et al., 2010).

A second series of experiments aimed at testing the hypothesis that at 7 months of age, when we have evidence of an ability to represent numerical order, the information of number is spatially oriented.

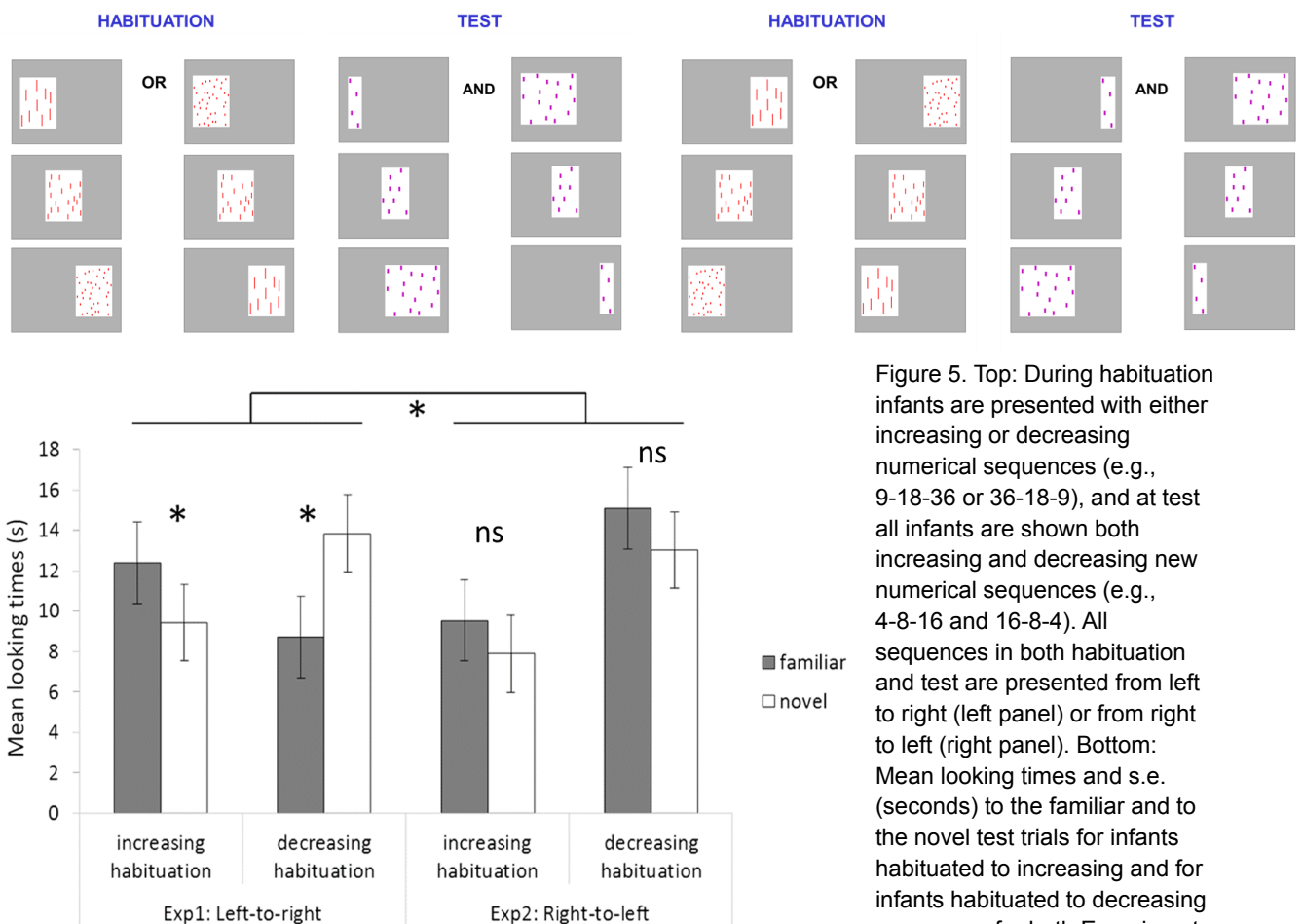


Figure 5. Top: During habituation infants are presented with either increasing or decreasing numerical sequences (e.g., 9-18-36 or 36-18-9), and at test all infants are shown both increasing and decreasing new numerical sequences (e.g., 4-8-16 and 16-8-4). All sequences in both habituation and test are presented from left to right (left panel) or from right to left (right panel). Bottom: Mean looking times and s.e. (seconds) to the familiar and to the novel test trials for infants habituated to increasing and for infants habituated to decreasing sequences for both Experiment 1 (left-to-right orientation) and

Experiment 2 (right-to-left orientation). From de Hevia et al. (2014) Plos One.

We employed the same methods and materials as the study previously described, except that we presented the numerical arrays oriented from left to right (for both the increasing and decreasing series).

Under these conditions, both groups of infants, those habituated to increasing order (left-to-right oriented) as well as those habituated to decreasing order (left-to-right oriented), looked significantly longer to the new increasing (left-to-right oriented) numerical sequences at test. This pattern of performance was not replicated when the same numerical sequences were presented from right to left. Moreover, in the absence of numerical information, infants at the same age display equivalent amounts of attention towards a left-right and right-to-left oriented sequence, but show a baseline preference for an increasing left-to-right oriented numerical sequence (see Fig. 5). Overall, our findings show that infants take into account the specific association between numerical order and space. Moreover, we also provide evidence that infants display a preference for a specific coupling between these two types of information, numerical order on the one hand, and oriented spatial codes on the other, as indexed by their preference for numerical arrays progressively increasing in number and oriented from left to right (de Hevia, Girelli, et al., 2014).

Collectively, these studies offer preliminary hints for an early spatial organization of numerical information along a left-to-right horizontal axis.

Further evidence for a number-spatial position mapping comes from studies examining the presence of a SNARC-like effect in infants. We used a Posner-like attentional task (Posner, 1980) akin to those used in adults (Bulf et al., 2014; Fischer et al., 2003), in order to investigate whether a numerical cue would drive the allocation of visual attention in 8- to 9-month-old infants in the same way as they do in adults. We registered infants' eye movements while presenting lateralized targets that were preceded by central non-symbolic numbers (either small or large). We found that infants were faster at detecting targets appearing on the right when cued by large numbers, and targets appearing on the left when cued by small numbers (Bulf et al., 2016). This finding indicates that, as in adults, non-symbolic numbers induce attentional shifts towards a peripheral region of space that is congruent with the numbers' relative position along a left-to-right oriented mental number line, already during the first year of life.

## A (directional) number-spatial position mapping in newborns

Building from previous evidence of a number-spatial position mapping in infants (Bulf et al., 2016; de Hevia, Girelli, et al., 2014), as well as evidence showing that humans from birth associate representations of number and space (in the form of a number-spatial extent mapping), we asked whether the origins of the number-spatial position mapping are the result of an innate bias or whether it develops after birth.

We adapted the methodology used in the past to show that human newborns expect changes in magnitude to occur in the same direction across different dimensions (number-spatial extent mapping), adopting the same bimodal, cross-dimensional methodology (de Hevia, Izard, et al., 2014). Newborns were presented with congruent changes in magnitude across dimensions (auditory changes in magnitude were always accompanied by the expected, congruent changes in visual size); the critical test was whether the newborn preferred to view a decrease in auditory magnitude paired with the congruent decrease in visual size on the left and an increase in auditory magnitude paired with the congruent increase in visual size on the right, relative to the reverse mapping (de Hevia, Veggiotti, et al., 2017).

The paradigm had two phases: a familiarization phase (60 seconds) immediately followed by a test phase constituted by two trials. In a series of 5 experiments, we familiarized half the infants to a small quantity and the other half to a large quantity, paired with a centered geometric figure. We then tested



infants with the other quantity across two trials with a new geometric figure, presented once on the left and once on the right side of the screen. Infants familiarized with the small quantity were tested with the large quantity, while infants familiarized with the large quantity were tested with the small quantity. Newborns were thus stimulated with both quantities (small and large) across the experimental session from familiarization to test, which we assumed allowed them to infer relative quantities. We found that newborns do, in fact, possess the left-few/right-many bias, suggesting that an innate mechanism is at the basis of later behavior (e.g., adult SNARC effect). Critically, we found that this mapping is privileged for number, as we did not find it in other continuous magnitudes in either the auditory or visual modalities, and prevails even when controlling for duration and visual length (see Fig. 6). This suggests that the more general tendency to associate small magnitudes with the left and large magnitudes with the right side of space develops later, perhaps as a generalization of the innate number-space association.

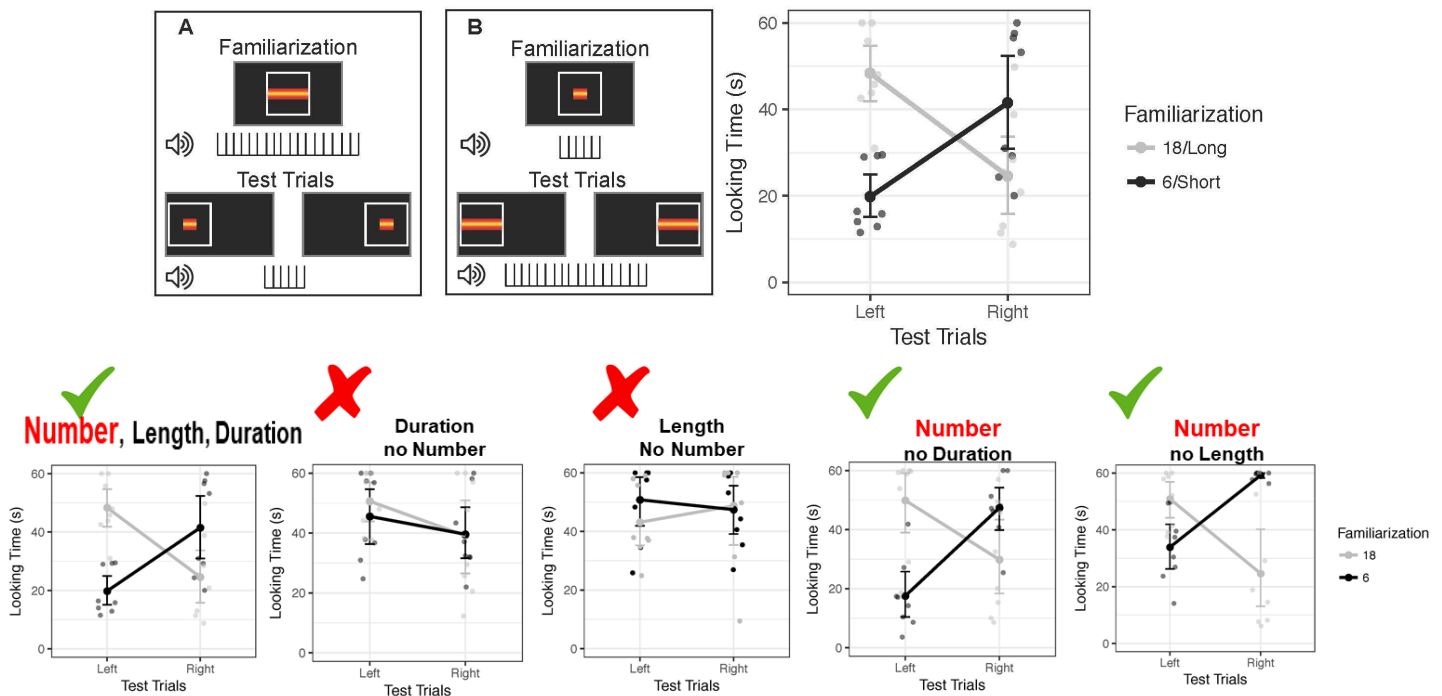


Figure 6. Top: A. Experiment 1, familiarization to 18-syllable sequences paired with a long line, moving stroboscopically but asynchronously with the syllables; Test trials with 6-syllable sequences paired with a short line appearing on the left in one trial and with a short line appearing on the right in another trial. B. familiarization to 6-syllable sequences paired with a short line, moving stroboscopically but asynchronously with the syllables; Test trials with 18-syllable sequences paired with a long line appearing on the left in one trial and with a short line appearing on the right in another trial. Newborns in condition A look longer to the left-sided line at test, whereas newborns in condition B look longer to the right-sided line at test, consistent with a small-left/large-right bias. Bottom: Experiments 2-5. The bias small/left-large/right is only present when the stimulus contains numerical quantity, and it is absent when duration and/or visual length are presented to newborns. From de Hevia, M.D., Veggiotti, L., Streri, A., & Bonn, C. (2017). At birth humans associate “few” with left and “many” with right. *Current Biology*, 27, 3879–3884.e2.

## (Ordinal) Operational Momentum in infants

Another way to look into the (directional) spatial signature of numerical representation consists of exploiting the phenomenon of operational momentum. Operational momentum (OM), which consists in overestimating outcomes to addition problems and underestimating outcomes to subtraction problems, is a special case of representational momentum, in which stimulus transformation is mapped onto motion in a spatial coordinate system, either physical or representational (McCrink et al., 2007). In OM, change in numerical magnitude is mapped onto movement along a mental number line: attention is shifted towards the right (larger numbers) for addition and towards the left (smaller numbers) for subtraction. This phenomenon is present even in preverbal infants (McCrink & Wynn, 2009), suggesting that attention distribution during arithmetic operations is not instantiated purely by culture or formal schooling, and instead may be intuitive and early-developing with little experience.

In collaboration with Koleen McCrink (Barnard College, US), and Hermann Bulf and Viola Macchi Cassia (University of Milano-Bicocca, Italy), we investigated whether a momentum phenomenon similar to the one generated by arithmetic operations is present also when infants represent increasing and decreasing relations among continuous magnitudes (i.e., physical size). Using an infant-controlled habituation paradigm, 80 infants (40 4-month-olds and 40 12-month-olds) were habituated to increasing or decreasing size-based sequences; in the test phase they were presented with an alternation of an against-momentum ordinal sequence and a with-momentum ordinal sequence (e.g., if habituated to an increasing size-based sequence, then the against-momentum sequence would be represented by an increasing series that contains elements with a smaller size than the ones observed during habituation; a with-momentum would contain an increasing series with larger elements than the ones observed during habituation). The presence of OM is inferred from infants' longer looking times to sequences that violate the momentum generated during habituation relative to sequences that follow the momentum.

While twelve-month-olds looked significantly longer at the against-momentum trials than at the with-momentum trials, 4-month-olds looked equally long at both ordinal test displays. By 12 months of age infants therefore show the momentum effect even when computing ordinal information for non-numerical continuous quantities. Momentum phenomena being interpreted as reflecting properties of spatial representation of a continuum, the presence of momentum for ordering size suggests that continuous quantities are represented spatially during the first year of life.

Another series of experiments investigated the presence of OM for ordinal relations in 4-month-old infants, who failed to present an OM phenomenon for size-based sequences. Since the (directional) number-spatial position mapping emerges first for numerical magnitude (Bulf et al., 2016; de Hevia, Veggioni, et al., 2017), and is later generalized to other magnitudes (Bulf et al., 2014; Gevers et al., 2003), we asked whether 4-month-olds would show evidence of an ordinal OM phenomenon when using numerical sequences. Infants were tested in an ordinal task in which they detected and represented increasing or decreasing variations in numerical size, and then responded to ordinal sequences that exhibited greater or lesser numerosities, thus following or violating the OM generated during habituation. Results showed that OM was present provided both number and continuous magnitudes were available cues to discriminate between with-OM and against-OM sequences during test trials. The presence of momentum for ordering number only when provided with multiple cues of magnitude changes suggests that OM is a complex phenomenon that blends multiple representations of magnitude early in infancy.

## 4.5. Origins of a number-spatial position mapping: asymmetries in ordinal processing and spatial attention

Do humans internally create number-spatial position mappings as a consequence of being exposed to cultural artifacts such as number lines, abacuses and graphs, and by receiving formal math instruction? Some argued that, because of the cultural variability in the number-spatial mapping, which can be modulated depending on the specific, culturally-driven, attentional biases (Dehaene et al., 1993; Zebian, 2005), the development of a numerical representation in spatial terms would emerge first in the form of a number-spatial extent mapping, and that only later, after repeated exposure to cultural habits that direct attention in a specific orientation, the number-spatial position would follow (de Hevia & Spelke, 2009). The hypothesis we have put forward (de Hevia, 2016b, 2016a, 2021; de Hevia, Girelli, et al., 2012) is that the origins of the tendency to spatialize information with a specific directionality, which has been found in non-human animal species (Drucker & Brannon, 2014; Rugani et al., 2015; Rugani & de Hevia, 2017) might have its roots in early biases concerning the processing of space and of seriality.

### Ordinal abilities in human infants: asymmetrical processing

A series of studies conducted with 4-month-old infants have investigated the properties of ordinal discrimination at this young age using non-numerical magnitude information: size-based sequences. We conducted a series of experiments that have provided evidence that this ability is functional at 4 months of age. Critically, we systematically found an asymmetry in ordinal discrimination performance, with successful discrimination of increasing sequences accompanied by a failure for the discrimination of decreasing sequences (Macchi Cassia et al., 2012). In another study, using the same methods and testing infants of the same age, we have replicated the asymmetry in ordinal processing when using numerical information, supporting the view of a common (or at least parallel) development of the ordinal ability for the dimensions of number and size.

We presented 4-month-old infants during habituation with either increasing or decreasing numerical sequences and were then tested with both orders (Fig. 7). We found that only infants that were habituated to the increasing numerical sequence were able to discriminate between increasing and decreasing numerical sequences at test; in contrast, infants habituated to decreasing numerical sequences did not show any differential looking times at test trials (de Hevia, Addabbo, et al., 2017). Although one might argue that, in order for infants in the increasing habituation condition to successfully discriminate between the familiar and novel sequences at test, successful abstraction of decreasing order must occur, we think this is not the case. Infants might discriminate increasing from decreasing order at test without truly representing the ordinal information conveyed by the decreasing test sequence: this might be simply represented as a collection of different numerical sets, with no encoding of the directionality of the change.

It is worth noting that we have gathered evidence that by 7-8 months of age, this asymmetry is not present anymore in studies using the habituation paradigm (de Hevia & Spelke, 2010; Picozzi et al., 2010). However, we believe the asymmetry in ordinal processing observed in the first months of life might be at the basis of more mature phenomena that permeate numerical cognition even in adulthood, which is the relative advantage for addition computation relative to subtraction (Barth et al., 2006, 2008). Moreover, we have suggested (de Hevia, Addabbo, et al., 2017) that the asymmetry in computing order might find its roots in perceptual/attentional mechanisms that are present in humans from birth: the

attentional boost effect produced by looming stimuli (Ball & Tronick, 1971; Náñez, 1988) (i.e., stimuli that when approaching oneself increase in size), which might find its roots in our evolutionary history.

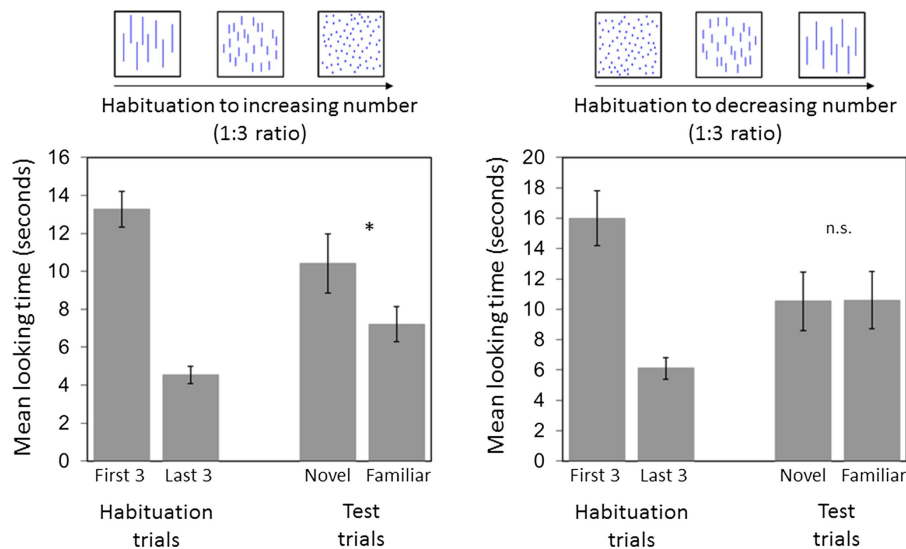


Figure 7. Mean total looking time ( $\pm$ SE) to the first three and last three habituation trials and to familiar and novel test trials for infants in the increasing (left) and decreasing (right) habituation conditions. Numerical displays differed by a 1:3 ratio. From de Hevia et al. (2017). *Cognition*.

In our view, this asymmetry offers another piece of information to the understanding of the origins of the left-to-right oriented number line: the advantage for the increasing order, together with the existence of biologically-determined attentional biases (i.e., more attention deployed to the left hemisphere) could participate in the emergence of a spatially oriented numerical representation (de Hevia, Girelli, et al., 2012).

## Asymmetrical processing of space in infants and newborns

In line with our findings that humans from birth selectively map few to left and more to right (de Hevia, Veggioni, et al., 2017), we have proposed an evolutionary theory of the mental number line (de Hevia, 2016b, 2021; de Hevia, Girelli, et al., 2012) according to which a bias to initially fixate on the left side of space is paired with a bias to prefer sequences that increase in magnitude, and thus it is in part a spatial bias that yields lateralized processing of number seen in infancy. Several theorists have posited the existence of an innate visual processing advantage for the left side of space (Bowers & Heilman, 1980; Kinsbourne, 1970), due to the left visual hemifield being preferentially processed by the right hemisphere of the brain. There is evidence of a left hemifield advantage in infancy for stimuli such as faces, and patterns (de Schonen & Mathivet, 1990; Deruelle & de Schonen, 1995, 1998).

We started asking whether this left visual advantage is functional in the very first days of life, forming the basis for interactions with the world from birth, and providing a key component for the early mental number line (McCrink et al., 2020). The paradigm had a familiarization phase (60 s) immediately followed by a test phase (two trials). During familiarization, each newborn heard auditory sequences of syllables, either 6 or 18 syllables, paired with a centered, rotating visual star. Test trials contained the

same auditory stimulus as familiarization, now paired with a visual numerical array, presenting the numerosity that matched the auditory stimulus on the left on one trial and on the right on the other trial. We reasoned that if newborns present a left visual advantage, then they would fixate longer to a visual stimulus when its left side contained the same numerical magnitude as an auditory numerical sequence, as opposed to when the same stimulus was inversely oriented. We have found a general preference for fixating the visual stimulus whose left side numerically matched the auditory numerical sequence. This finding constitutes preliminary evidence for human newborns spontaneously privileging the left side of visual stimulation, and extends previous findings of this phenomenon in older infants for faces and patterns to numerical/quantity information.

As a related study on the origins of attentional asymmetries, we have investigated in collaboration with Elena Nava, Hermann Bulf and Viola Macchi Cassia (University of Milano-Bicocca, Italy) the bisection performance on a computerized task with eye tracking measurements in 4- to 5-month old infants (Nava et al., 2022). We trained infants to look at the objective center of a horizontal line, by providing the bisecting bar and a positive reward when their gaze was on a central area of the stimulus. During the test phase, infants were presented with similar horizontal lines, except that the bisecting bar was absent. We found that when presented with horizontal bars, infants fixated more to the left side with respect to the center, and this occurred both in the training and test phase, suggesting that even when infants had a cue signaling the bar midpoint, they nonetheless displayed a leftward bias. This result adds new evidence to the notion that functional asymmetries are already present very early in life and seem to support a more invariant model of lateralization, by which the infant brain presents adult-like brain and functional specializations that remain quite stable throughout development.

## 4.6. Functionality of a (directional) number-spatial position mapping

We first tested in adult participants the hypothesis that a spatial lay-out offers humans a useful mental framework to represent non-spatial information (e.g., organizing, coding and remembering any type of sequence which needs to preserve order information). Previous work showed that a mental, directional mapping on space would apply to any ordinal information: for instance, the classification of letters of the alphabet, months of the year, and pitch height, would derive in SNARC-like effects, by which the first elements of the series would be responded faster with the left hand, and the last elements of the series would be responded faster with the right hand (Gevers et al., 2003, 2004; Rusconi et al., 2006).

However, we hypothesized something more extreme: that even for a series of elements that is not-overlearned, in contrast to the series employed in past studies, subjects would strategically organize that information in a left-to-right oriented continuum provided that order is relevant. Thus, we investigated whether spatial coding of ordinal information can be constructed 'online', whenever elements' order is critical to the task. We asked adults to memorize a list of unrelated words, and later tested them on a series of order-relevant and order-irrelevant tasks. We observed the presence of SNARC-like effects when subjects were asked to classify each word as coming before/after a given one. Moreover, subjects showed SNARC-like effects when the task requested subjects to decide whether in the word of an image there was a given phoneme (the phoneme monitoring task). Therefore, when adults were requested to learn a list of unrelated words (never seen before in that particular order) they would spontaneously map them in an oriented spatial continuum. The activation of this spatial representation, moreover, was automatic, since participants would access it even when the order of the list was irrelevant to the task at hand (Previtali et al., 2010).

We next addressed the question of the functional role of mentally organizing non-spatial information in space in preverbal infants, in collaboration with Prof. Hermann Bulf and Prof. Viola Macchi Cassia from University of Milano-Bicocca. Our previous findings showed that 7- to 9-month-old infants' learning of ordinality in numerical sequences is critically impacted by the direction with which the sequences are provided. Infants are able to discriminate numerical ordinal direction when sequences of numerical displays are presented in the center of the screen (Picozzi et al., 2010) or from left to right (de Hevia, Girelli, et al., 2014), but not when presented from right to left (de Hevia, Girelli, et al., 2014). We asked whether, as in adults, the left-to-right oriented mapping would generalize to sequences that are not inherently ordered but for which the ordinal information is learned 'on-line'. In particular, we tested whether directional spatial information (left-to-right vs. right-to-left) would modulate preverbal infants' learning of any type of ordered sequences, especially when order is not an intrinsic feature but one that is coded and learned during task execution. We presented 7-month-old infants with rule-based visual sequences of geometrical shapes, manipulating the complexity of the rule (ABB vs. ABA) and the spatial orientation of the sequences (left-to-right vs. right-to-left) (Fig. 8).

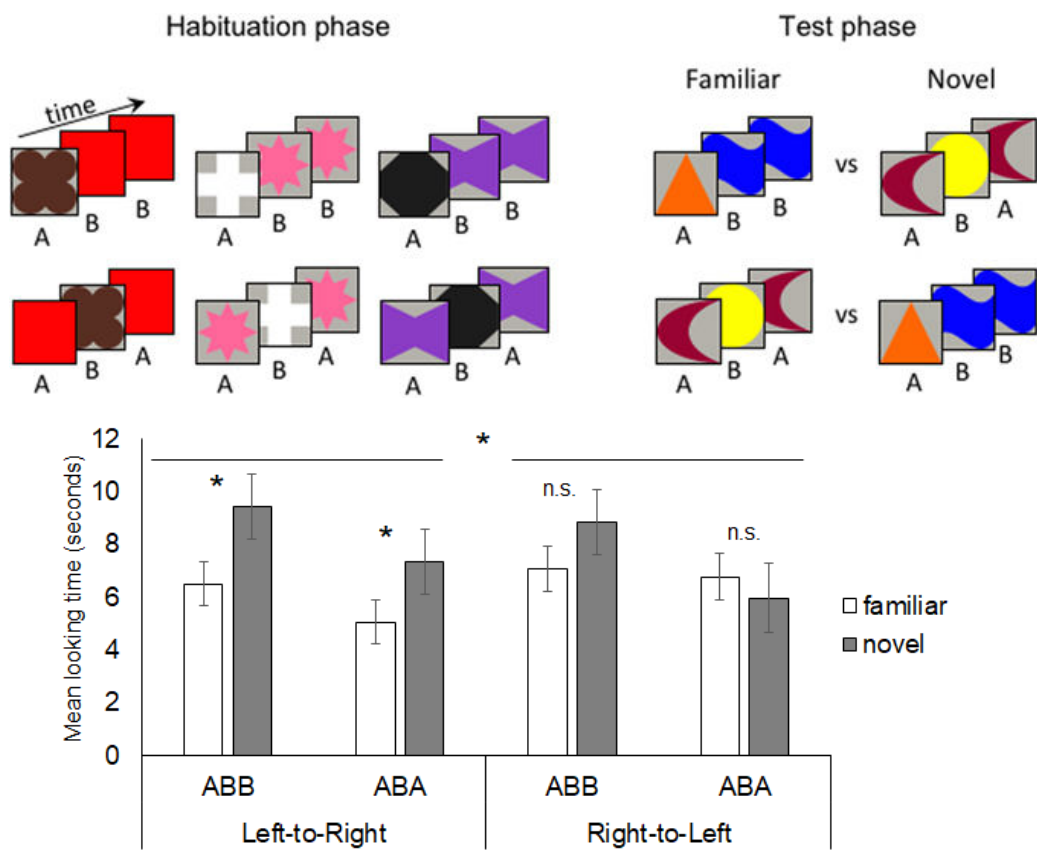


Figure 8. Top: Examples of the stimuli used during the habituation and the test phases. The shapes within each triplet were presented sequentially on the screen, from left to right in Experiment 1, and from right to left in Experiment 2. Half of the infants in each experiment were habituated to ABB rule-like sequences, whereas the other half were habituated to ABA rule-like sequences. Bottom: Mean looking times ( $\pm$ SE) to the familiar and to the novel test trials for infants presented with left-to-right oriented sequences in Experiment 1 and for infants presented with right-to-left oriented sequences in Experiment 2. Infants in Experiment 1 showed significantly longer looking times to the novel test trials than to the familiar test trials, whereas infants in Experiment 2 failed to discriminate between the two. From Bulf, H., de Hevia, M.D., Gariboldi, V., Macchi Cassia, V.M. (2017). Infants learn better from left to right: a directional bias in infants' sequence learning. *Scientific Reports*, 7.

We found that 7-month-old infants were able to detect the new rule at test in rule-like patterns following both ABB and ABA rules when sequences were presented from left to right, but failed with a right-to-left spatial orientation. This finding indicates that infants' rule learning abilities are strongly impacted by directional spatial information. In fact, earlier studies have shown that, in the absence of spatial information (i.e., when visual sequences are presented centrally on the screen), infants at this same age can extract and learn the ABB rule but fail with the more complex ABA rule with elements represented by visual geometric shapes (Johnson et al., 2009). Therefore, infants' success at learning the ABA rule with a left-to-right orientation demonstrates that this spatial orientation boosts infants' rule learning, whereas infants' failure at learning the ABB rule with a right-to-left orientation demonstrates that this spatial orientation hinders this ability (Bulf et al., 2017).

Collectively, these results suggest that the propensity to mentally spatialize information is present in the first years of life, following a specific directionality, indicating that online coding of serial information in working memory spontaneously operates on a spatial structure. This mental, spatial framework might be an optimal solution that allows inferring the order of each sequence element with minimal computation.

In more recent experiments we have been able to address the abstract nature of the generalized rule, by presenting 7-month-old infants with numerical information during the learning phase and testing their generalization capacity with geometrical figures. Critically, we manipulated the spatial arrangement of the information (left-to-right oriented vs. right-to-left oriented), as well as the direction of numerical change (i.e., increasing vs. decreasing) so that numerical order within the sequences could be either congruent or incongruent with the preferred left-to-right orientation of increasing order (de Hevia, Girelli, et al., 2014). We reasoned that, if a left-to-right spatial layout boosts infants' ability to extract ordinal information from visual sequences and a right-to-left spatial layout hinders such an ability, infants should learn and generalize abstract rules from left-to-right oriented numerical sequences, and should fail to do so with right-to-left oriented sequences, irrespective of the direction of the numerical change within the sequences. We found that infants were able to learn the rules only when the sequences followed a left-to-right orientation, and failed with a right-to-left orientation, as previously shown (Bulf et al., 2017). In addition, we found that the nature of this phenomenon is truly abstract, as infants were able to learn a rule in one domain (numerical) and transfer learning to a different one (geometrical figures). Finally, we found that during rule/ordinal learning, the orientation in space, in particular left-to-right oriented, overrides a correspondence between numerical magnitude and order in the form of a the left-small vs. right-large association, as infants behaved in similar ways with sequences oriented from left to right irrespective of their increasing or decreasing numerical order (Bulf et al., 2022).

This last finding, together with the presence of number-specificity at birth and infancy for SNARC-like behavior, led us to hypothesize that the two properties that the number-spatial position mapping can convey, quantity and ordinality, are internally spatialized leading to two different phenomena (de Hevia, 2021). On the one hand, quantity-induced lateralized (left vs. right) spatial biases, and on the other hand, ordinality-induced preferred directionality (e.g., left-to-right oriented) spatial biases. This dichotomy is observed from the first months of life (Bulf et al., 2016; de Hevia, Girelli, et al., 2014), and each of these mappings carries processing advantages. The quantity-induced mapping can modulate visuo-spatial target detection by speeding up attention towards the left when processing a small number and to the right when processing a large number (Bulf et al., 2014, 2016), so that 'relatively small' and 'relatively large' are respectively linked to 'left' and 'right' spatial codes (de Hevia, Veggiotti, et al., 2017; Di Giorgio et al., 2019). The ordinality-induced mapping not only reflects a preferred spatial directionality in ordinal processing, left-to-right oriented, but can directly modulate learning of ordinal relations for any sequence (Bulf et al., 2017, 2022; de Hevia, Girelli, et al., 2014).

# Conclusions

The ability to discriminate and represent information of magnitude is foundational to human reasoning. Are quantity representations available early in life so that they can have a determining role in structuring subsequent experience? Or are they extracted by learning mechanisms following exposure to a richly structured physical world? How is a spatial framework deployed to mentally represent these magnitudes? In order to address these questions, in my research I argue that the 'mental number line' model considers numbers as analogical representations on a spatially oriented continuum, involving two types of number-space mappings: numbers correspond to varying spatial extents and to lateralized spatial positions.

In my research I have provided evidence that number, length, and spatial arrangement are intimately related in human cognition. When we think of numbers, even if unconsciously, we map them onto spatial magnitudes and positions. This phenomenon affects our thinking: external number-space mappings (e.g., abacus, rulers, the real number line) might reflect internal, inborn mental number-space mappings (and not the other way around). The number-space mappings are independent of language, may be universal across cultures, and have possibly evolved from our ancestral history in the form of innate numerical and spatial biases, predisposing us to ground numerical representations on spatial dimensions from birth.

## 5. Five main activities as a PI

### 5.1. Jacobs Foundation Research grant. Project: Understanding numbers: Exploring the relation between numerical and spatial representations. P.I.: Maria Dolores de Hevia.

In this project, I proposed to conduct the first studies on the spatial properties of number on preverbal infants at Harvard University. The results of these studies were published in the journals *Psychological Science* and *Cognition*.

### 5.2. Fyssen Foundation Research grant. Project: The Realm of Magnitude Representations: Origins and Neural Basis. P.I.: Maria Dolores de Hevia.

In this project, I proposed to explore the nature and the neural basis of the links across different magnitude dimensions in human newborns. The results of these studies were published in *PNAS* and *Plos One*.



### 5.3. ANR JC/JC, Agence Nationale de la Recherche. Project: The Realm of Magnitude Representations: Origins and Neural Basis. P.I. (coord): Maria Dolores de Hevia.

In this project, I proposed to explore the nature and the neural basis of the links across different magnitude dimensions in human newborns. Most of this grant allowed hiring a postdoc for 1 year. The results of these studies were published in *Current Biology*, *PNAS* and *Plos One*.

### 5.4. ANR PRC, Agence Nationale de la Recherche. Project: Numbers in Action: Origins and Developmental Course. P.I (coord): Maria Dolores de Hevia.

In this ongoing project, I have proposed to explore for the first time in a developmental population the link number and action understanding. The first results have been presented at various conferences and a first paper is 'in press' in the journal *Scientific Reports*. Most of this grant has allowed hiring a postdoc for 1.5 years.

### 5.5. Thomas Jefferson Foundation (France-USA). Project: The origins and development of the mental timeline. P.I. France: Maria Dolores de Hevia.

In this recently funded project, I have proposed to explore for the first time the origins of the link between time and space in newborns and infants in partnership with the University of Washington (P.I. USA: Ariel Starr). This project will allow a collaboration with an USA partner, which involves an exchange of graduate and postdoc students, as well as the organization of workshops in both countries.

## 6. Capacity to lead research

As part of my second postdoc funded by a *Fulbright* fellowship, and a *MBB Harvard* fellowship (beginning 2006 - end 2009, Harvard University, USA), I started developing research on the origins of the mental number line building from my PhD work. This research was pioneering at the time, and contributed the first pieces of evidence for the building blocks of a mental number line in a developmental population (de Hevia, Vandervelde, et al., 2012; de Hevia & Spelke, 2009, 2010, 2013). Until then, the origins of this numerical-spatial representation were thought to be culturally-dependent and arising only in late childhood. Moreover, with this work we provided evidence that non-symbolic numerical representations are mapped onto corresponding spatial extents, highlighting as well the existence, early in life, of different ways to map number onto space.

As part of my third postdoc funded by a *Marie-Curie* fellowship (2012-2014, NeuroSpin and Universite de Paris, France) I pushed forward the investigation of the origins of number-space mappings in humans by testing newborns in a maternity ward. We showed that at birth, humans create expectations of congruency for magnitude changes across the dimensions of number and spatial extent, providing evidence of a number-spatial mapping functional at birth (de Hevia, Izard, et al., 2014). Subsequent work, as a CNRS researcher, was the first to disclose the presence of a small-left and large-right association in humans at birth (de Hevia, Veggiotti, et al., 2017). This work provided evidence that both a number-spatial extent mapping and a number-spatial position mapping are functional at birth, only after a few hours after birth.

Since my recruitment by the CNRS (2015-on, INCC) I have received funding from various agencies as a PI to further pursue my research agenda:

2021. *Thomas Jefferson Foundation* (France-USA), 20.000\$. Project: The origins and development of the mental timeline. P.I. France: Maria Dolores de Hevia (Universite de Paris), P.I. USA: Ariel Starr (University of Washington).

2019. *ANR PRC, Agence Nationale de la Recherche*, France, 433.518 €. Project: How Domain-general Functions Contribute to the Development of Numerical Competencies. P.I.(coordinator): Andre Knops; co-P.I. (partner): Maria Dolores de Hevia.

2019. *ANR PRC, Agence Nationale de la Recherche*, France, 179.047 €. Project: Numbers in Action: Origins and Developmental Course. P.I. (coordinator): Maria Dolores de Hevia.

2016. *ANR JC/JC, Agence Nationale de la Recherche*, France, 109.304 €. Project: The Realm of Magnitude Representations: Origins and Neural Basis. P.I. (coordinator): Maria Dolores de Hevia.

2015. *Fyssen Foundation*, 21.500 €. Project: The Realm of Magnitude Representations: Origins and Neural Basis. P.I.: Maria Dolores de Hevia.

During my career at different institutions in Italy, USA and France, I have mentored and supervised research work at different levels, from students spending formative periods in the lab, to master students as well as PhD and postdoctoral students:

## Mentoring and Research Supervision

### (2004 - 2015)

Supervision and examination of undergraduate dissertations on numerical processing in adults and infancy, Facoltà di Psicologia, *Università di Milano-Bicocca*, Italy (7 students).

Research training and supervision of undergraduate research projects on studies on infants and children's understanding of number, Laboratory for Developmental Studies, *Harvard University*, USA (4 students).

Research training and supervision of master students' research projects on studies on newborns' and infants' understanding of number, space and time, *Laboratoire Psychologie de la Perception, University Paris-Descartes*, France (4 students).

### (2015 - today)

#### *Master students:*

Maria Eirini Netskou: Master student M1 2015-2016 and M2 2016-2017 (2 publications)

Marie Pagny: Master student M1 2016-2017

Alice Debost: Master student M1 2016-2017  
 Elena Kerjean: Master student M1 2016-2017  
 Schaines Flih: Master student M1 2017-2018  
 Loona Charbonneau: Master student M1 2017-2018  
 Nerea Jimenez Deza: Master student M1 2019-2020  
 Burcu Onaran: Master student M2 2019-2020  
 Laetitia Le Bras: Master student M2 2019-2020  
 Hafsa Aït Ougram: Master student M1 2021-2022 and M2 2022-2023

*Trainees:*

Ludovica Veggiotti: from 04/15/2016 - on (4 publications, 3 conferences)  
 Yu-Na Lee: MIT-France program, summers of 2016 and 2017 (1 publication)  
 Lionel Cohen: 08/12/2017 - 13/04/2018  
 Sarah Hausberger: 19/02/2018 - 13/03/2018  
 Lucile Jarielle: 03/04/2018 - 04/05/2018  
 Eloise West: Columbia University, summer of 2018  
 Salma Bennani: 12/11/2018 - 28/12/2018  
 Laura Spath: June and July 2019  
 Sabrina Jimenez: June and July 2019  
 Morgane Edelin: 09/09/2019 - 03/02/2020  
 Caroline Mourtialon: 21/09/2020 - 09/10/2020  
 Estelle Lehongre: 12/02/2020 - 17/04/2020 (partly interrupted by COVID-19 pandemic)  
 Ariel Lesmana: 25/01/2021 - 30/04/2021  
 Louis Bourgaux: 19/04/2021 - 01/08/2021 (1 publication)  
 Heidi Sainte-Catherine: 01/06/2021 - 27/08/2021  
 Louise De Schuytter: 01/06/2021 - 26/06/2021  
 Cloe Cabos: 14/06/2021 - 07/07/2021  
 Loeiza Gourvès: 14/06/2021 - 07/07/2021  
 Manon Marchais: July 2021  
 Eponine Asselin: September - October 2021  
 Margot Jouzel: 01/10/2021 - 31/01/2022  
 Gwenn Pennaneac'h: October 2021  
 Naila Illikoud: October 2021 - June 2022  
 Dana Azoulay: January - April 2022  
 Chloé Borry: January - April 2022  
 Fatima Kassem: January - March 2022  
 Celize Salzillo: Erasmus program w/University of Milano-Bicocca, March - October 2022

*PhD students:*

Andrea Adriano: 01/09/2021 - 31/01/2022 (visiting student from University of Milano-Bicocca, funded by an Erasmus fellowship; now postdoctoral researcher at Neurospin, Saclay, France)

*Postdoctoral students:*

Nawal Abboub: 01/01/2016 - 31/12/2016 (funded by my ANR JC/JC NUMSPA; now co-Founder of *Rising up*, Paris, France) (2 conferences)  
 Cory D. Bonn: 01/09/2016 - 31/12/2017 (Fyssen postdoctoral fellow; now Data Scientist at *Strong Analytics*, Chicago, US) (2 publications)  
 Gisella Decarli: 01/06/2021 - on (funded by my ANR PRC NUMACT) (1 publication, 3 conferences)

In addition to the scientific articles in which I have been the *leading/first author* of the research (19; see list of publications), I have served as *senior author* for 11 *peer-reviewed articles* (idea conceptualization, supervision of data collection and analyses, co-writing of paper with first author):

- Macchi-Cassia, V., Picozzi, M., Girelli, L., & **de Hevia**, M.D. (2012). Increasing magnitude counts more: Asymmetrical processing of ordinality in 4-month-old infants. *Cognition*, 124, 183-193.
- Viarouge, A., & **de Hevia**, M.D. (2013). The role of numerical magnitude and order in the illusory perception of size and brightness. *Frontiers in Cognition*, 4, 484.
- Bulf, H., Macchi-Cassia, V.M., **de Hevia**, M.D. (2014). Are numbers, size and brightness equally efficient in orienting visual attention? Evidence from an eye-tracking study. *PLOS One*, 9, e99499.
- Macchi Cassia, V.M., Bulf, H., McCrink, K., & **de Hevia**, M.D. (2017). Operational Momentum during ordering operations for Size and Number in 4-month-old Infants. *Journal of Numerical Cognition*, 3, 270-287.
- McCrink, K., & **de Hevia**, M.D. (2018). From innate spatial biases to enculturated spatial cognition: The case of spatial associations in number and other sequences. *Frontiers in Psychology-Developmental Psychology*, 9, 415.
- Bonn, C.D., Netskou, M.E., Streri, A., & **de Hevia**, M.D. (2019). The association of changes in brightness with changes in number/duration in human newborns. *PLOS One* 14(10): e0223192.
- McCrink, K., Veggiotti, L., & **de Hevia**, M.D. (2020). A left visual advantage for quantity processing in neonates. *Annals of the New York Academy of Sciences*, 1477(1), 71-78.
- Viarouge, A., & **de Hevia**, M.D. (2021). Can a single representational object account for different number-space mappings? *Frontiers in Human Neuroscience*, section *Cognitive Neuroscience*, 15:750964.
- Viarouge, A., & **de Hevia**, M.D. (under review). What activates a shared representation underlying number-location and number-size associations?
- Decarli, G., Veggiotti, L., & **de Hevia**, M.D. (in press). The link between number and action in human infants. *Scientific Reports*.
- Decarli, G., Rama, P., Granjon, L., Veggiotti, L., & **de Hevia**, M.D. (in preparation). Disclosing the link between number and action in 3-month-old infants using electrophysiological methods.

I have been *senior supervisor* for 14 *conference presentations* (talks and posters; see list of publications/conferences).

I have served as *secondary supervisor* for 10 articles:

- Previtali, P., **de Hevia**, M.D., & Girelli, L. (2010). "Placing order in space: The SNARC effect in serial learning". *Experimental Brain Research*, 201, 599-605.
- Picozzi, M., **de Hevia**, M.D., Girelli, L., & Macchi Cassia, V. (2010). "Seven-month-old infants detect ordinal numerical relationships within temporal sequences". *Journal of Experimental Child Psychology*, 107, 359-367.
- Perrone, G., **de Hevia**, M.D., Bricolo, E., & Girelli, L. (2010). "Numbers can move our hands: A spatial representation effect in digits handwriting". *Experimental Brain Research*, 205, 479-487.
- Chinello, A., **de Hevia**, M.D., Geraci, C., & Girelli, L. (2012). Finding the SNARC in signed numbers: Notational effects in accessing number representation. *Functional Neurology*, 27, 177-185.
- Bulf, H., **de Hevia**, M.D., & Macchi Cassia, V.M. (2016). Small on the left, large on the right: Numbers orient preverbal infants' visual attention onto space. *Developmental Science*, 19, 394-401.
- Bulf, H., **de Hevia**, M.D., Gariboldi, V., Macchi Cassia, V.M. (2017). Infants learn better from left to right: a directional bias in infants' sequence learning. *Scientific Reports*, 7.

- Dunn, H., Bernstein, N., **de Hevia**, M.D., Macchi Cassia, V., Bulf, H., & McCrink, K. (2019). Operational Momentum for Magnitude Ordering in Preschool Children and Adults. *Journal of Experimental Child Psychology*, 179, 260-275.
- Bulf, H., Capparini, C., Nava, E., **de Hevia**, M.D., & Macchi Cassia, V. (2022). Space modulates cross-domain transfer of abstract rules in infants. *Journal of Experimental Child Psychology*, 213, 105270.
- Nava, E., **de Hevia**, M.D., Bulf, H., & Macchi Cassia, V. (2022). Signatures of functional visuospatial asymmetries in early infancy. *Journal of Experimental Child Psychology*, 215, 105326.
- Bourgau, L., **de Hevia**, M.D., & Charras, P. (accepted, pre-registered report). Spatio-numerical mapping in 3D: is horizontal mapping the best candidate? *Experimental Psychology*.

## Motivation for applying to the HDR

This application is motivated, first, by the wish to supervise PhD students, to accompany them for a longer period of time in their higher education (comparably, postdoctoral students usually spend shorter periods of time), and enable them to pursue a career in the field of research and/or higher education, if they wish. Second, the HDR degree constitutes a natural, additional step in the progression of my career, and will allow me to apply for a CNRS Research Director position in the future.

## 7. Research Projects

The ability to discriminate and represent information of magnitude is foundational to human reasoning. We, and many species of non-human creatures, use this ability in everyday experiences, such as estimating the number of people attending a dinner; it allows us and other animals to decide whether the best bet when facing a group is to attack or to escape, and it also intervenes when one needs to calculate the time available to complete an action. Understanding the functional mechanisms of this fundamental cognitive ability is at the core of my research program.

The last decades of studies on the functional properties of numerical representations have started to shed light into this domain. For instance, the representational correspondences between number and space (a small number evokes a short length and the left spatial position, a large number long and right), which I have contributed to highlight, may afford us insight into how the domain of number is structured and reasoned about. From an applied perspective, since number knowledge is at the center of mathematics instruction, and math skills is one of the best predictors of later academic performance (Duncan et al., 2007), our knowledge of how number is represented, understood, and the intuitions that guide reasoning about it, is essential for the design of early childhood programs that promote academic skills.

In what follows, I present a few lines of future research that build on mine and others' work.

## 7.1. Functionality of number-spatial mappings

One of the most pressing questions regarding the understanding of number-spatial mappings is their functionality. Why would it be advantageous to map numbers onto different spatial dimensions (extent and location)? One could argue that, because we humans possess a 'mental number line' in which we organize numerical information with a given directionality, the observation of SNARC-like effects might represent only 'side-effects' when activating this type of representation. However, I'll argue that a functional role cannot be discounted. In fact, evidence for number-spatial position mappings in non-human animals (Drucker & Brannon, 2014; Rugani et al., 2015) and humans at birth (de Hevia, Veggioni, et al., 2017; Di Giorgio et al., 2019) might indicate that this phenomenon has a functional role, instead of just having an arbitrary character.

### Number-spatial extent mapping

The number-spatial extent mapping conveys advantageous quantity processing: when both number and spatial extent are congruent (e.g., both are large or small), decision making regarding both magnitudes speeds up as well as increases in accuracy (Hurewitz et al., 2006). It is possible that this advantage is due to a stronger magnitude representation, in a sort of inter-dimensional redundancy (akin to 'intersensory redundancy', Bahrick & Lickliter, 2000): numerical and spatial magnitudes might be combined at some representational, perhaps adimensional, level. The question whether information from different 'quantity' sources are bound together in a decision making stage or in a common, single representation warrants further research. While neuroimaging studies in adults have shown that the common parietal areas recruited in both numerical and spatial length representation do not exhibit signatures of a shared representation (Borghesani et al., 2019; Harvey et al., 2015), future neuroimaging studies in infants will shed light on whether these separate representations derive from learning to parcel out an original common representation, or not.

We have started to address this question in human infants using the fNIRS technique. Preliminary analyses have shown a significant difference between the alternating (when stimulation includes changes in numerosity) and non-alternating (numerical identity is constant) blocks in parietal regions of the neonate brain. This result nicely fits with literature on the neural basis of number, which consistently identifies the parietal cortex as the locus for processing this type of information, mainly in the right hemisphere (Cantlon, 2018), and suggests developmental continuity in the cortical areas subserving numerical discrimination. Future studies need to establish whether cortical activity in the neonate brain engaged in processing other quantitative dimensions, such as temporal duration and spatial extent, is both quantitatively and qualitatively similar.

Studies on human infants have shown that using multiple cues to magnitude representation can boost numerical processing. In fact, the ability to represent large numerosities in an approximate way develops in precision until adulthood following specific ratios: newborns need a 1:3 ratio difference between two sets to differentiate them (Coubart et al., 2014; de Hevia, Izard, et al., 2014; Izard et al., 2009), 6-month-old infants a 1:2 ratio, 9-month-olds a 2:3 ratio, and adults are able to tell apart 9 vs. 10 (Halberda et al., 2012; Lipton & Spelke, 2004; Xu & Spelke, 2000). While 4- to 5-month-old infants need a ratio between 1:3 and 1:2 to discriminate between numerical sets (de Hevia, Addabbo, et al., 2017; Wood & Spelke, 2005), recent evidence shows that 4-month-olds' performance in numerical discrimination tasks improves when concurrently presenting them with both visual and auditory numerosities (Wang & Feigenson, 2021), as well as with multiple cues -both numerical and non-numerical- (Macchi Cassia et al.,

2017). Future studies are needed to shed light on the conditions that allow the formation of a stronger numerical representation in studies of humans from birth and across the first months of life. These studies are fundamental to understanding the malleability of numerical acuity, the potentiality to improve it, as well as the mechanisms by which numerical cognition blends a variety of magnitude cues from the first months of life.

## Number-spatial position mapping

The two properties that the number-spatial position mapping can convey, quantity and ordinality, are internally spatialized leading to two different phenomena. On the one hand, quantity-induced lateralized (left vs. right) spatial biases, and on the other hand, ordinality-induced preferred directionality (e.g., left-to-right oriented) spatial biases. This dichotomy is observed from the first months of life (Bulf et al., 2016; de Hevia, Girelli, et al., 2014). I'll argue that each of these mappings carries processing advantages.

The *quantity-induced mapping* can modulate visuo-spatial target detection by speeding up attention towards the left when processing a small number, and to the right when processing a large number (Bulf et al., 2014, 2016; Fischer et al., 2003), so that 'relatively small' and 'relatively large' are respectively linked to 'left' and 'right' spatial codes at birth, both in humans (de Hevia et al., 2017; Di Giorgio et al., 2019), and non-human species (Rugani et al., 2015). Why would such a bias be functional from birth? At this point, I can only speculate on the functionality of lateralized processing of numerical magnitude, and while recent attempts to account for it have been made (Felisatti et al., 2020; Vallortigara, 2018), future research is still needed for a comprehension of this phenomenon.

A possibility I would like to put to test is that the quantity-induced mapping might have its (perhaps functional) roots in hemispheric asymmetries related to attentional control and object representation. Attention is directed more easily to the side of space contralateral to the more activated hemisphere, and the right hemisphere is specialized in spatial attention (Kinsbourne, 1970). On the other hand, object directed attention is mainly modulated by the number of objects that can be tracked, with only 3-4 distinct objects being individuated in parallel (Scholl, 2001). If the priority is to track the properties of individuals forming a set, then not only selecting the smaller set but also linking it to the left hemifield could be the best option. Conversely, selecting the larger set and linking it to the right hemifield would happen when the priority is to analyze the set as a whole. This is a purely speculative idea that needs to be fully explored in future research, in particular whether functional specialization for visuo-spatial processing is lateralized to the right hemisphere at birth (see McCrink et al., 2020; Nava et al., 2022, for our first attempts). For now, the available evidence of an advantage in processing and modulation of spatial attention towards the left when processing a small number and to the right when processing a large number is congruent with the idea that these might constitute only 'side effects' with no specific function. Along these lines, it has been recently proposed that the quantity-induced mapping originates from the asymmetric tuning of the brain for different spatial frequencies (SFs), so that the SFs contained in small vs. large sets engage respectively the right vs. left brain hemisphere, resulting in the left vs. right lateralized responses (Felisatti et al., 2020). However, this account fails to explain findings of SNARC in newborns using auditory numerosities, as well as the absence of a SNARC with visual size (de Hevia, Veggioni, et al., 2017); more generally, this account needs to explain the presence of SNARC with symbolic numbers, and non-numerical stimuli, as an item list (Previtali et al., 2010), for which a SF account by itself would not suffice.

Future studies will aim at testing the idea that attentional control and object representation limits are at the basis of lateralized representations of number early in life. Eventually, this account would need to include a characterization of the process by which this phenomenon would apply, later in life, to 'any' numerical range (i.e., a smaller vs. larger number distinction is relative, not absolute, as my account on object-limit processing would predict), to other non-numerical dimensions, such as size (Bulf et al., 2014; Ren et al., 2011), or memorized items (Gevers et al., 2003; Previtali et al., 2010). The proposal to test is that the building blocks of hemispheric asymmetries related to attentional control and object representation consist of evolutionary constraints in information processing, which would later generalize to a whole range of symbolic and non-symbolic domains in humans through processes of similarity and analogy (Gentner & Markman, 2006), by virtue of their abstract, common features as quantitative and/or ordinal dimensions.

The *ordinality-induced mapping* not only reflects a preferred spatial directionality in ordinal processing, left-to-right oriented, but can also directly modulate learning of ordinal relations. While 7-m-o infants can learn the increasing and decreasing order in numerical sequences (Picozzi et al., 2010), they fail to do so when the sequences are presented spatially arranged from right to left, although the ability is retained when presented from left to right (de Hevia, Girelli, et al., 2014). Interestingly, infants fail to learn ordinal information when numbers appearing in decreasing order are presented from right to left (i.e., largest on the right, middle on the center, smaller on the left), despite this numerical-spatial arrangement being coherent with the quantity-induced mapping (small-left and large-right). This finding suggests that the two mappings reflect different cognitive operations. Indeed, the ordinality-induced mapping is not number-specific, but instead seems to reflect a general, functional property of working memory whereby ordinal/serial information is coded within a spatial framework. Infants' learning of serial order is boosted when visual sequences are explicitly presented in spatial positions from left to right, and hindered when presented from right to left (Bulf et al., 2017; de Hevia, Girelli, et al., 2014), relative to a central presentation (Johnson et al., 2009; Picozzi et al., 2010), indicating that online coding of serial information in working memory spontaneously operates on a spatial structure (McCrink & Shaki, 2016; Previtali et al., 2010). This mental, spatial framework might be an optimal solution that allows inferring the order of each sequence element with minimal computation.

Do humans internally create a spatial framework to mentally represent sequences as a result of postnatal experience in a world that is highly spatialized? Evidence of a preferred spatial orientation in both numerical and non-numerical sequences in human infants (Bulf et al., 2017, 2022; de Hevia, Girelli, et al., 2014) downplays the role of education and symbolic knowledge. However, cultural factors do not necessarily come in the form of reading/writing, which are acquired in late childhood, but also from the influence caregivers exert by directing attention in space to young children (McCrink et al., 2018). A recent cross-cultural study has shown that the culturally-dependent modulation of visuo-spatial attention is already present in 7-m-o infants (Macchi Cassia et al., 2020). This account could therefore explain the number-spatial position mapping in Western, 7- to 8-month-old infants: they systematically look longer when a series of increasing numbers appear one after the other aligned onto a left-to-right oriented spatio-temporal mapping (e.g., first 8 dots/left side, then 16 dots/center, and finally 32 dots/right side) vs. when the spatial mapping is reversed, i.e., right-to-left oriented (de Hevia, Girelli, et al., 2014). Future studies will test the presence for the ordinality-induced mapping at birth -note that this differs from the quantity-induced mapping disclosed at birth (de Hevia, Veggiotti, et al., 2017; Di Giorgio et al., 2019)-, and will aim at describing its developmental course during the first months of life.

An additional puzzle I would like to address is the finding of an asymmetrical nature of ordinal processing coupled with the presence of ordinal OM for both increasing and decreasing order at 4 months of age. Our previous OM studies (Macchi Cassia et al., 2017) suggest that a stronger representation was



built by infants while viewing increasing, relative to decreasing, order during habituation, and that additional cognitive resources were devoted to the representation of decreasing ordinal relations, compared to increasing, for both numerical and size-based sequences. This pattern in performance is well in line with the asymmetry in ordinal sensitivity for infants the same age that we have described: ordering increasing magnitudes enjoys an advantage over ordering decreasing magnitudes both for size (Macchi Cassia et al., 2012) and number (de Hevia, Addabbo, et al., 2017). However, infants at this age show an OM effect for both increasing and decreasing ordinal relations. More specifically, the strength of the OM effect was comparable for both increasing and decreasing (i.e., no ordinal asymmetry), and OM was present for arrays of discrete elements (i.e., number) but not for single shapes varying in size (Macchi Cassia et al., 2017). How can these patterns of performance be reconciled? The finding that ordering operations and momentum effects exhibit different behavioral signatures suggests that these operations might tap on (at least partially) different cognitive mechanisms. If one assumes that the OM phenomenon signals the overshoot of attention along a spatial representation, then the findings suggest that at 4 months a spatially oriented framework is involved during computation of numerical sequences -only when multiple magnitude cues are available- but absent for size. This would nicely fit with the presence of SNARC-like effects for number but not for size at birth (de Hevia, Veggiotti, et al., 2017), and later in infancy (Bulf et al., 2016); by 12 months of age, we have found that infants show an OM effect when representing size (Macchi Cassia et al., 2016), suggesting that by the first birthday a spatial mental framework might apply as well to representing variations in size. Future studies are needed to establish a more precise developmental pattern of the emergence of the OM effect for both numerical and non-numerical quantities, so as to shed further light on the nature of infants' magnitude representations. Future studies need to clarify whether an ordinal numerical representation is indeed underlying OM effects. This project is in progress.

For parts of this ongoing project we have secured funding from the Agence Nationale de la Recherche (France, ANR PRC), 433.518 €. How Domain-general Functions Contribute to the Development of Numerical Competencies. P.I.(coordinator): Andre Knops; co-P.I. (partner): Maria Dolores de Hevia.

## 7.2. Mappings across quantitative and ordinal dimensions: from uniqueness to general-purpose

What exact role space plays in the conceptual structure of other magnitude/ordinal domains, and when, how and why we map them onto space represent core questions of my research project.

### Number-spatial extent mapping

Considering the number-spatial extent mapping an instance of a more general ability to relate quantitative, or prothetic, dimensions -which can be experienced as 'more than' and 'less than' (S. S. Stevens, 1957)-, relates to the proposal of a generalized magnitude system (Walsh, 2003) according to which these dimensions share a common representation, code or metric. However, I have argued that the number-spatial extent mapping might be privileged across human development. *First*, in adults numerical magnitude affects the estimation of spatial extent, with underestimation vs. overestimation for small vs. large numbers, respectively (de Hevia et al., 2008), but this numerical effect does not generalize to the estimation of brightness level (Viarouge & de Hevia, 2013). *Second*, preschool children easily create number-spatial extent mappings, but are at chance for number-brightness mappings (de Hevia,

Vanderslice, et al., 2012). *Third*, infants are not as flexible as adults in linking different dimensions to one another: using the same methods, preverbal infants map number to spatial extent (de Hevia & Spelke, 2010) but not number to brightness level (de Hevia & Spelke, 2013); they map duration to spatial extent, but not loudness to spatial extent (Srinivasan & Carey, 2010). *Fourth*, newborns show a preference when number and spatial extent change in the same direction (both increase or both decrease) and disprefer situations in which these dimensions change in opposite directions (one increases the other decreases) (de Hevia, Izard, et al., 2014); however, they are more flexible for concurrent changes in number and brightness, being willing to accept both changing contexts (Bonn et al., 2019).

Despite evidence for a privileged number-spatial extent mapping from birth through the first years of life, eventually adults seem to effortlessly relate changes across quantitative dimensions; what is the developmental course of this ability, which appears to be functional at the earliest in late childhood (de Hevia, Vanderslice, et al., 2012)?

## Number-spatial position mapping

The number-spatial position mapping extends to other quantitative and non quantitative, ordinal dimensions in adults, but not all of these dimensions have comparable effects on visuo-spatial processing and attention. For quantitative dimensions, while passive viewing of small and large numbers, as well as small and large objects, prime adults' attention to the left and right sides of space, respectively, variations of brightness do not exert the same effect (Bulf et al., 2014). With respect to ordinal dimensions, while adults spontaneously organize the first items on the left and the last items on the right side of space for a list of memorized words, as well as letters of the alphabet and months of the year, incidentally seeing these elements does not suffice to spatially orient attention, but explicit access to their ordinal status is required (Dodd et al., 2008; Previtali et al., 2010). One possibility for the primacy of number on visuo-spatial processes is that it is the prototypical ordered sequence and its spatial representation might be overlearned. However, this account cannot be generalized to findings of this phenomenon in preverbal infants and to the use of non-symbolic numbers (Bulf et al., 2016).

Eight-month-old infants detect a left target faster when primed with a centered, small non-symbolic number than when the prime is a large number, and detect faster a right target when primed by a large, relative to a small, non-symbolic number; however, this attentional advantage is number-specific and, unlike in adults, does not extend to size (Bulf et al., 2016), despite infants being competent in processing size variations (e.g., de Hevia & Spelke, 2010). This numerical specificity does not depend on experience: at birth, humans prefer to attend to the left side of space for a small numerosity and to the right side of space for a large numerosity; however, when presented only with duration and/or spatial length, the preference for lateralized spatial positions vanishes (de Hevia et al., 2017). Future studies are needed to understand whether the number-spatial position mapping is number-specific at birth in other species as well.

It is worth noting that the argument I have put forward, of a privileged number-spatial extent mapping, depends largely on a contrast between number-brightness vs. number-space mappings. However, there is some evidence to suggest that infants may relate other dimensions to one another, like space and pitch (Dolscheid et al., 2014; Walker et al., 2010). For instance, infants look longer at a ball moving upwards when accompanied by a rising pitch than when accompanied by a falling pitch (Walker et al., 2010). One key aspect to understand is whether the horizontal axis (left vs. right) is specific for number at birth and/or whether it extends to a vertical dimension (top vs. bottom) as well; conversely, the question whether pitch height can be mapped as well onto a horizontal axis is still open. Finally, similarly

to the number-spatial extent mapping, infants may relate pitch and object size (Fernández-Prieto et al., 2015); however, only older infants seem to create this association, suggesting that experience might play an important role in establishing this mapping, and supporting the view of a privileged number-spatial extent mapping in human cognition. Further studies are needed that systematically investigate the presence/absence of different mappings using the same methods at birth and across the first months of life.

In summary, the privilege status of both number-spatial mappings is in place from birth, and is therefore independent of the environment and/or education; across development, different quantitative/ordinal dimensions are mapped to each other, and/or to an oriented space, possibly via processes of similarity and analogy (Gentner & Markman, 2006), based on their shared functional nature as quantitative and ordinal dimensions. An objective of future research is to understand, and describe, the specific developmental course by which the privileged number/time-space mappings develop eventually into a general-purpose mechanism, with mappings generalizing to any quantitative dimension and ordinal sequence. More studies are thus needed to establish both the timing and the processes involved in the generalization of mappings across quantitative dimensions. Future research should provide, as well, an account for the specificity of numerical-spatial mappings that permeates cognition across development; one candidate might be found in the (possible) functionality of number-space mappings, which are found at birth and possibly have evolutionary origins that I discussed more in detail in the previous section.

### 7.3. Towards a unified account on the origins and development of number-space mappings

A number of pressing questions regarding the origins and developmental course of number-space mappings are still open. What do we start with, and how do we get to a mature form of number-space mapping? I have made in the past previous attempts (de Hevia, Girelli, et al., 2012; McCrink & de Hevia, 2018; Rugani & de Hevia, 2017), still incomplete, to try and provide a clear picture on these questions. As part of my research agenda, starting to shed some light on these open problems is of central importance. Here I present some of them.

#### *Single, common representation at birth for number, size and duration*

Findings on newborns' mappings across number, spatial extent and duration (de Hevia, Izard, et al., 2014) are congruent with the possibility of a single, common and indistinguishable representation for these dimensions at birth (Walsh, 2003), which would become differentiated with development, starting at the latest in childhood (Odic, 2018). It is certainly a possibility that representations of different quantitative dimensions are bound together at a certain level of abstraction. However, findings in newborns showing that a relative increase/decrease is associated with a right vs. left spatial position, respectively, and that this association does not apply to size nor to duration (de Hevia, Veggiotti, et al., 2017), suggest that numerical representations at birth retain a specificity/singularity that is not shared with these other dimensions. Moreover, the cross-dimensional mappings that are functional at birth might be relative or absolute. Humans might possess at birth a sort of calibration mechanism that allows them to pair dimensions of number, size and duration provided that changes across them follow the same ratio (i.e., all increase/decrease following a 1:3 ratio); another possibility is that the mappings are established on coarse magnitude changes (i.e., the only prerequisite for mappings to be established is that dimensions change in the same direction, even if the magnitude of the change -e.g., 1:3 ratio for one vs. 1:6 ratio for the other- are not the same). Finally, it is not clear yet whether the number-spatial extent mapping is a

symmetrical or an asymmetrical link, although infant studies suggest the link is symmetrical at this early developmental age, as they can generalize equally well from number to spatial magnitude and vice versa (Lourenco & Longo, 2010), and newborns' mappings (de Hevia, Izard, et al., 2014) are also congruent with them being bidirectional, supporting the view of a symmetrical link early in life. On the other hand, in the ordinality-induced, number-spatial position mapping the relationship seems to be asymmetric, as space is thought to provide a mental framework for working memory.

*Timeline for directional mappings: when and how different spatial orientations emerge*

The idea of a universal, biological left-to-right orientation leads to the prediction that at birth, and perhaps during the first months of life irrespective of cultural environment, the left-to-right orientation would, at the very least, co-exist with the other(s) orientation(s), and that change would emerge across development and be related to specific experiences with the new directionality (Pitt & Casasanto, 2020). Another prediction is that infants/toddlers/children who are born with a left-to-right oriented mapping might have difficulties to adapt to their right-to-left mapping environment and overcome an innate left-to-right bias. No studies have tested this possibility yet. However, we know that different, opposite mappings might coexist and cancel each other, at least in adults (Shaki et al., 2009).

Moreover, available studies suggest that the developmental timeline of the number-spatial position mapping appears to be complex. Although these mappings are described in childhood and adulthood, there is still no evidence of continuity from birth through early childhood, as if these phenomena observed early in life would vanish later in development. In fact, the toddler years constitute a particularly flexible period in development in which number-spatial position mappings could be somehow 'dormant' (McCrink & de Hevia, 2018). Along these lines, one explanation of these inconsistencies lies on the use of implicit measures, like looking time in infancy, and active choice methods from the toddler years, which could reflect that although the ability might be present the 'strength' of knowledge required in explicit measures is greater (see Mix et al., 2016). In fact, some studies show evidence of a left-to-right mapping of number in preschoolers depending on the task (e.g., present for object counting, magnitude comparison task with non symbolic numerosities vs. absent for numerosity arrangement tasks and finger counting) (Patro & Haman, 2012, 2017). These inconsistencies underscore the fluctuating nature of this effect at this age, as well as the incompatibilities that emerge from using different tasks. These caveats call for a unified use of methodologies that would allow the establishment of a complete developmental timeline.

There is likely an interplay of factors that could be determinant for the emergence and consolidation of number-space mappings in the early years of life. For instance, some studies have shown that biomechanical factors (i.e., the hand used to perform the actions) can modulate the way children act in space in specific numerical tasks (van't Noordende et al., 2017). This evidence has been noted in the past by other researchers even in Western adults who, for instance, despite showing a left-to-right oriented number line, tend to start counting on their right hand (Fischer, 2008). I believe, however, these data cannot definitely tell us what spatial properties the internal representation of number has, but reveal that, with development, the orientation of visuospatial attention, which guides our actions and mental representations (Bisiach & Luzzatti, 1978), depends on biological (right hemispheric dominance), biomechanical (hand dominance), and cultural (reading habits) factors (Rinaldi et al., 2020). Further cross-cultural studies from birth through the first months of life are necessary to establish the developmental trajectory of different number-spatial position mappings.

Another key issue is the development of dichotomic small/left and large/right associations vs. the development of a spatial directionality applied to sequences. While I have argued that the former is privileged for number at birth (de Hevia, Veggiotti, et al., 2017), and in infancy (Bulf et al., 2016), the latter seems to be a general-purpose strategy which is functional by 7-8 months of age (Bulf et al., 2017, 2022). Future studies need to determine whether the spatial directionality applies to any sequence at birth (this question is presented in 6.4. for the case of time). Furthermore, this differentiation (i.e., a dichotomic left/right vs. a spatial directionality) could account for some findings of an apparent absence of a spatial directionality in preschool children (Guida et al., 2020). One crucial aspect present in the findings of spatial directionality in infants is that the ordinal sequences to be represented were formed by more than two items (Bulf et al., 2017, 2022; de Hevia, Girelli, et al., 2014), whereas other studies asked younger children to memorize only two items (Guida et al., 2020). Given that spatialization of ordinal information is thought to boost learning and memory so as to infer the order of an item with minimal computation, this strategy might not be needed when memorizing only two items. The fact that older children and adults might show a left-to-right spatialization of two items might indicate that their habit of spatializing information is overlearned and automatically applied to any condition. Finally, dichotomic left/right lateralization of information in humans at birth (de Hevia, Veggiotti, et al., 2017), infancy (Bulf et al., 2017, 2022) and early childhood (Patro & Haman, 2012), as well as in non human animals (Adachi, 2014; Rugani et al., 2015) has always been strictly related to numerical information, whereas studies in preschool children used non numerical information (the names of two animals; Guida et al., 2020).

#### *Universal vs. cultural variation of spatial directionality*

The idea of an innate left-to-right mapping is supported by evidence for number-space mappings in non-human animals and humans at birth. For instance, non-human primates exhibit a spontaneous left-to-right oriented mapping of counting (or serial order) (Drucker & Brannon, 2014), and are faster in responding to a small number when is on the left and to a large number when is on the right (Adachi, 2014). These findings have been reported in evolutionary distant species such as chicks as well (Rugani et al., 2010, 2015; Rugani & de Hevia, 2017, for a review). However, studies have shown that there is cultural variation in the spatialization of number (i.e., left-to-right oriented in Western cultures and right-to-left oriented for readers/writers of Arabic, Farsi and Hebrew, for instance). This idea received support from the observation that the canonical orientation in Western cultures, left-to-right oriented, is mitigated or even reversed in participants with right-to-left reading/writing habits (Dehaene et al., 1993). Therefore, the left-to-right orientation must be malleable to accommodate variations across cultures or task settings; for instance, when Western adults imagine numbers in a clock face the mapping takes a right-to-left orientation (Bächtold et al., 1998). Nevertheless, in Western adults the left-to-right directionality emerges in spontaneous circumstances and is hard to completely reverse (Pitt & Casasanto, 2020), and adults with opposite reading/writing directions show the same association of more, and addition, with the right, and less, and subtraction, with the left side of space (Masson et al., 2020), underscoring the continuity of biological factors and of early biases present at birth.

The idea of a default, universal left-to-right orientation predicts that illiterate adults should show this phenomenon as well. However, absence of spatial representation of serial order has been recently described in illiterate Arabic adults (Guida et al., 2018), disconfirming this prediction. However, illiterate adults can differ from literate adults in many practices, beyond reading/writing abilities. For instance, illiterate adults might have generated along the years a myriad of techniques to memorize ordinal information, possibly different from literate adults, given that they lack the same symbolic abilities (techniques perhaps even more sophisticated in visuo-spatial terms in illiterate adults, possibly using a combination of spatial axes). More importantly, in this study Arabic illiterate adults were tested. This population lives in a context where the right-to-left orientation is the predominant one (as the study

shows). One can consider that illiterate adults begin at birth with a (default) left-to-right oriented mapping that is counteracted by the right-to-left culture they live in. Since they did not acquire the reading/writing abilities that explicitly direct visual and motor action in space in a systematic way, their case might be similar to the transient period in which toddlers and preschoolers are when they start being influenced by cultural conventions but have not yet acquired reading/writing abilities (McCrink & de Hevia, 2018). Another possibility is that the spatialization effect in illiterate Arabic adults could be canceled out given the two coexisting orientations. This is in line with studies showing that Israelis do not show a consistent spatial mapping of Arabic numerals, as the two orientations (the one determined by their predominant scanning habit, right-to-left, and the one with which they spatially write and read Arabic digits, left-to-right) canceled each other out (Shaki et al., 2009). This hypothesis predicts that Western, illiterate adults living in a left-to-right culture should maintain their 'default' left-to-right orientation, but future studies should be conducted to put this prediction to test.

In order to support research on these overarching projects (6.1., 6.2., and 6.3.) I plan to apply to funding agencies, including the Agence Nationale de la Recherche (ANR) and the Jacobs Foundation in the coming years.

## 7.4. Origins and developmental course of the mental timeline

In many cultures, adults represent time using a mental timeline, a model of time based off of a linear reference. For example, in Western cultures, time is mapped onto a horizontal axis with a left-to-right orientation with earlier events represented on the left and later events on the right (Bonato et al., 2012; Ishihara et al., 2008). This orientation is influenced by cultural conventions such as writing direction, and in other cultures it is oriented right-to-left or top-to-bottom (Ouellet et al., 2010). Adults automatically reference this mental timeline when remembering or reasoning about the temporal order of events (Santiago et al., 2007, 2010).

A critical question concerns the origins of the mental timeline. Are we naturally inclined to think about time in terms of space, perhaps due to shared neural substrates in the parietal cortex, or do we learn to think about time in terms of space as a result of the culture we grow up in? We plan to investigate the origins of the mental timeline in human newborns and infants, and delineate its developmental trajectory in children and adults as well.

Although the mental timeline has been extensively studied in adults, few studies have focused on children. In addition, these prior studies have all required some form of explicit response, e.g., children may be asked to place stickers on a sheet of paper to represent the order of events (Tillman et al., 2018). These designs have limited use for very young children and infants who cannot yet understand verbal instructions or make explicit responses. However, a number of studies have used eye-tracking measures to examine spatial associations in infants. These studies used looking time as an index of whether infants associate different dimensions with one another. Results from this method have shown that infants spontaneously associate longer spatial extents with longer temporal durations and larger numerosities (de Hevia, Izard, et al., 2014; Srinivasan & Carey, 2010). In addition, studies have shown that infants (Bulf et al., 2014; de Hevia & Spelke, 2010), and even neonates in their first few days of life (de Hevia, Veggiotti, et al., 2017; Di Giorgio et al., 2019), associate smaller numbers with the left side of space and larger numbers with the right. These studies demonstrate that not only do infants map space to other domains, but they may also do so with a specific preferred orientation.

The findings that infants associate space with other dimensions and that these associations may have a specific orientation suggest that experience with cultural tools is not necessary to form these associations. Do these spatial associations also extend to infants' representations of temporal order? To answer these questions, we will use a violation of expectation paradigm with looking time (neonates, infants) and pupillometry (infants, children and adults) to probe the development of the mental timeline between birth and adulthood. Participants will view triplets of images. The triplets will be presented sequentially from left-to-right, right-to-left, top-to-bottom, or non-linearly. After a brief familiarization period, the original triplets will be interspersed with oddball triplets in which the temporal order is violated (eg ACB instead of ABC). If participants are spontaneously representing temporal order using a mental timeline, then oddballs of the nonlinear triplets should elicit smaller responses (change in looking time or pupil dilation) than oddballs of the linear triplets. Furthermore, if participants are orienting the mental timeline from left-to-right, then deviants from this arrangement should elicit the largest response. A key strength of this design is that it requires no explicit responses -the dependent variables are based on eye-tracking metrics-, which enables us to use similar stimuli and paradigms across age groups in order to assess continuity and change in the development of the mental timeline.

If the tendency to associate time and space is biologically determined, then we would expect that even neonates in the first few days of life would show evidence for an association between them. Consistent with number-space mappings, neonates might also show a preference for a left-to-right orientation over others. Note that although previous studies with neonates have shown a bias for few-left and many-right, this association was not present for temporal duration (i.e., short vs. long events) (de Hevia, Veggioni, et al., 2017). However, in the proposed studies we will test a different temporal aspect: episodic memory, whereby events take place before or after one another. We might also expect that this orientation preference will strengthen as children gain increasing exposure to cultural practices that explicitly spatialize time. Alternatively, the mental timeline might be a cultural invention, such that it only emerges after children have had exposure to relevant cultural practices and artifacts. The mental timeline therefore provides an ideal test case for probing how biology and culture contribute to the origins of abstract thought. This project just kicked off.

For this project we have secured funding from the Thomas Jefferson Foundation (France-USA), 20.000\$. Project title: The origins and development of the mental timeline. P.I. France: Maria Dolores de Hevia (Universite de Paris), P.I. USA: Ariel Starr (University of Washington).

## 7.5. Numbers and Action

In the last few years the view that the motor system is exclusively dedicated to the control of actions has been challenged, suggesting that it contributes critically to conceptual processes such as those involved in language and mathematics (Barsalou, 2008; Lakoff & Núñez, 2000). In the case of number, it has been suggested that sensorimotor experience plays an important role, with symbolic numbers conveying meaning if they are mapped to our perceptual and/or motor experiences (Andres et al., 2008). Moreover, an influential view during the last decade has put forward the argument that the neural organization of the inferior parietal cortex reflects the common need for information of magnitude (i.e., number, space, time) to be used in the sensorimotor transformations needed for action, that are the main goal of these cortical areas (Walsh, 2003). Studies with human adults have indeed revealed that numerical processing impacts the planning and execution of motor actions, and vice versa, actions such as pointing and grasping exert an influence in numerical processing during the adult years (Ranzini et al., 2022). It has been suggested that the motor system responsible for grasping is endowed with processes that automatically take into account the magnitude estimates conveyed by numbers: small grip aperture

actions are initiated faster in the presence of small numbers and large grip aperture actions are initiated faster for large numbers (Andres et al., 2004), the size of graspable objects is overestimated or underestimated according to the magnitude of numbers (Badets et al., 2007), and observing a closing or opening grip influences the magnitude of the numbers produced in a number generation task (Badets et al., 2012).

Critically, only a few developmental studies have investigated the number-action link. Since finger movements often co-occur with number recitation during acquisition of counting, and persists into adulthood (Di Luca et al., 2006), it has been suggested that the involvement of motor circuits in numerical processing constitutes a trace of the finger-counting strategies used in childhood (Butterworth, 1999). Moreover, it has been shown that the ability to identify the fingers touched by an experimenter, without visual feedback, is a better predictor of 6-year-old's mathematical skills than standard developmental tests (Noël, 2005). Therefore, the motor system is actively engaged in numerical processing by the time children spontaneously start using finger counting strategies. However, since adjacent areas in the parietal cortex host both numerical processing and visuo-motor abilities from very early in life (Hyde et al., 2010; Izard et al., 2008; Wilcox et al., 2010), it is reasonable to predict that the number-action coupling might emerge very early in development, well before the use of finger counting strategies during childhood. In line with this hypothesis, it has been suggested that action understanding relies on evolved, domain-specific mechanisms for interpreting and predicting the actions of others (Wood et al., 2007; Woodward, 1998), and that certain abstract assumptions, including a principle of efficiency, are available as innate constraints on this action perception system (Carey, 2000; Liu et al., 2017, 2019; Skerry et al., 2013; Skerry & Spelke, 2014). Efficiently taking into account the physical constraints of the environment by the action system, such as information of size, distance, position and number, carries great advantages from an evolutionary point of view. Our action system might thus have evolved by incorporating sensitivity to magnitude information that is functionally available early in life. Magnitude information (i.e., number, size, time) makes for an ideal candidate of a (possibly innate) constraint available to the action perception system.

Despite the evidence for spatial and motor aspects related to numerical cognition in the adult brain and the impact of this discovery on cognitive and clinical psychology and neuropsychology, the origins and development of this phenomenon have been largely neglected and remain almost unsolved. We will investigate the origins and developmental course of the link between numbers and action by asking the following core questions. *First*, is there an early link between numbers and action in humans? In particular, are humans, already from birth, able to meaningfully match information of magnitude (i.e., size, number) with an observed action? Does this ability extend to other dimensions of magnitude, such as temporal duration? *Second*, when and how interpreting others' actions takes advantage of the information of magnitude? In particular, are infants able to predict the goal of an agent using the information of number? Do they react to the (lack of) congruency between an action and a related magnitude? *Third*, when and how infants' brain reflects a number-action link? In particular, is infants' electrophysiological activity modulated by congruent vs. incongruent number-action couplings?

This project will use behavioral and electrophysiological measures in human newborns and infants, by describing when and how the action perception system is sensitive to, and efficiently incorporates, information of number. Behavioral looking time and eye movement paradigms will test for the early presence of a number-action link, and the ability to detect and anticipate the goal of an action using numerical information (see Fig. 9 and 10). Electrophysiological paradigms will be used to investigate modulations of infants' EEG activity during the observation of congruent and incongruent number-action couplings. This project is in progress.



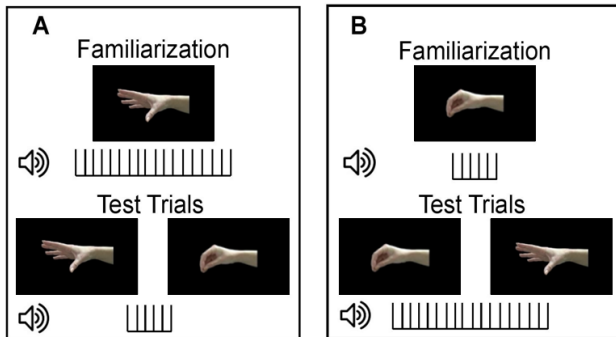


Figure 9. Example of experimental stimuli and design used with newborns. In analogy to the methods used in the past with spatial extent, here we will use a hand action (open, close) to convey magnitude about an action. We will test whether newborns expect that a large number accompanied by a large action (top A) is followed by a small number and a small action (bottom right A).

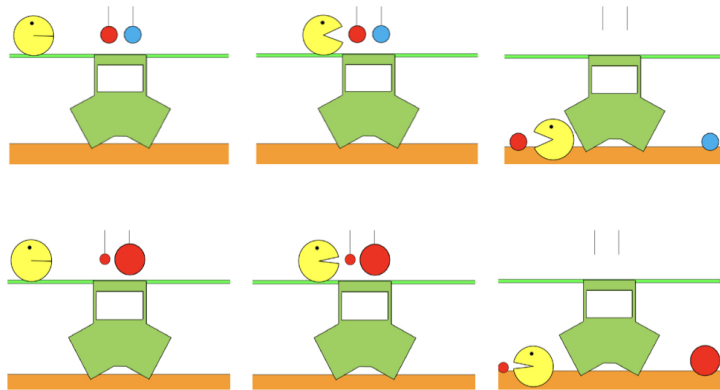


Figure 10. Example of experimental stimuli and design used for the eye-tracking method. Top: Images of familiarization videos where Pacman moves towards two hanging balls, which fall into the tube, exiting on the left and right sides. Pacman enters the tube and reaches the red ball. Bottom: Images of the test videos where Pacman moves towards a small and a big ball; the two objects fall into the tube. In congruent trials, Pacman exits from the side of the tube where there is the congruency between mouth and object's size. In incongruent trials, Pacman exits from the side of the tube where the size of the ball is incongruent with his mouth.

This ongoing project has been funded by the Agence Nationale de la Recherche (France, ANR PRC), 179.047 €. Project: Numbers in Action: Origins and Developmental Course. P.I.: Maria Dolores de Hevia.

## References

- Adachi, I. (2014). Spontaneous Spatial Mapping of Learned Sequence in Chimpanzees: Evidence for a SNARC-Like Effect. *PLoS ONE*, 9(3), e90373. <https://doi.org/10.1371/journal.pone.0090373>
- Andres, M., Davare, M., Pesenti, M., Olivier, E., & Seron, X. (2004). Number magnitude and grip aperture interaction. *Neuroreport*, 15(18), 2773–2777.
- Andres, M., Olivier, E., & Badets, A. (2008). Actions, words, and numbers: A motor contribution to semantic processing? *Current Directions in Psychological Science*, 17(5), 313–317.
- Bächtold, D., Baumüller, M., & Brugger, P. (1998). Stimulus-response compatibility in representational space. *Neuropsychologia*, 36(8), 731–735.
- Badets, A., Andres, M., Di Luca, S., & Pesenti, M. (2007). Number magnitude potentiates action judgements. *Experimental Brain Research*, 180(3), 525–534.
- Badets, A., Bouquet, C. A., Ric, F., & Pesenti, M. (2012). Number generation bias after action observation. *Experimental Brain Research*, 221(1), 43–49.
- Bahrlick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Developmental Psychology*, 36(2), 190.
- Ball, W., & Tronick, E. (1971). Infant Responses to Impending Collision: Optical and Real. *Science*, 171(3973), 818–820. <https://doi.org/10.1126/science.171.3973.818>
- Barsalou, L. W. (2008). Grounded cognition. *Annu. Rev. Psychol.*, 59, 617–645.
- Barth, H., Beckmann, L., & Spelke, E. S. (2008). Nonsymbolic, approximate arithmetic in children: Abstract addition prior to instruction. *Developmental Psychology*, 44(5), 1466–1477. <https://doi.org/10.1037/a0013046>
- Barth, H., La Mont, K., Lipton, J., Dehaene, S., Kanwisher, N., & Spelke, E. (2006). Non-symbolic arithmetic in adults and young children. *Cognition*, 98(3), 199–222. <https://doi.org/10.1016/j.cognition.2004.09.011>
- Berch, D. B., Foley, E. J., Hill, R. J., & Ryan, P. M. (1999). Extracting Parity and Magnitude from Arabic Numerals: Developmental Changes in Number Processing and Mental Representation. *Journal of Experimental Child Psychology*, 74(4), 286–308. <https://doi.org/10.1006/jecp.1999.2518>
- Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex*, 14(1), 129–133.
- Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience & Biobehavioral Reviews*, 36(10), 2257–2273.
- Bonn, C. D., Netskou, M.-E., Streri, A., & de Hevia, M. D. (2019). The association of brightness with number/duration in human newborns. *PLOS ONE*, 14(10), e0223192. <https://doi.org/10.1371/journal.pone.0223192>
- Borghesani, V., de Hevia, M. D., Viarouge, A., Pinheiro-Chagas, P., Eger, E., & Piazza, M. (2019). Processing number and length in the parietal cortex: Sharing resources, not a common code. *Cortex*, 114, 17–27. <https://doi.org/10.1016/j.cortex.2018.07.017>
- Bowers, D., & Heilman, K. M. (1980). Pseudoneglect: Effects of hemispace on a tactile line bisection task. *Neuropsychologia*, 18(4–5), 491–498.
- Brannon, E. M. (2002). The development of ordinal numerical knowledge in infancy. *Cognition*, 83(3), 223–240.
- Bulf, H., Capparini, C., Nava, E., de Hevia, M. D., & Macchi Cassia, V. (2022). Space modulates cross-domain transfer of abstract rules in infants. *Journal of Experimental Child Psychology*, 213, 105270. <https://doi.org/10.1016/j.jecp.2021.105270>
- Bulf, H., de Hevia, M. D., Gariboldi, V., & Macchi Cassia, V. (2017). Infants learn better from left to right: A directional bias in infants' sequence learning. *Scientific Reports*, 7(1), 2437. <https://doi.org/10.1038/s41598-017-02466-w>
- Bulf, H., de Hevia, M. D., & Macchi Cassia, V. (2016). Small on the left, large on the right: Numbers orient visual attention onto space in preverbal infants. *Developmental Science*, 19(3), 394–401. <https://doi.org/10.1111/desc.12315>
- Bulf, H., Macchi Cassia, V., & de Hevia, M. D. (2014). Are Numbers, Size and Brightness Equally Efficient in Orienting Visual Attention? Evidence from an Eye-Tracking Study. *PLoS ONE*, 9(6), e99499. <https://doi.org/10.1371/journal.pone.0099499>
- Butterworth, B. (1999). *The mathematical brain*. Macmillan.
- Cantlon, J. F. (2018). How Evolution Constrains Human Numerical Concepts. *Child Development Perspectives*, 12(1), 65–71. <https://doi.org/10.1111/cdep.12264>
- Carey, S. (2000). The origin of concepts. *Journal of Cognition and Development*, 1(1), 37–41.
- Coubart, A., Izard, V., Spelke, E. S., Marie, J., & Streri, A. (2014). Dissociation between small and large numerosities in newborn infants. *Developmental Science*, 17(1), 11–22. <https://doi.org/10.1111/desc.12108>
- de Hevia, M. D. (2016a). Core mathematical abilities in infants. In *Progress in Brain Research* (Vol. 227, pp. 53–74). Elsevier. <https://doi.org/10.1016/bs.pbr.2016.04.014>
- de Hevia, M. D. (2016b). Link Between Numbers and Spatial Extent From Birth to Adulthood. In *Continuous Issues in Numerical Cognition* (pp. 37–58). Elsevier. <https://doi.org/10.1016/B978-0-12-801637-4.00002-0>
- de Hevia, M. D. (2021). How the Human Mind Grounds Numerical Quantities on Space. *Child Development*

- Perspectives*, 15(1), 44–50. <https://doi.org/10.1111/cdep.12398>
- de Hevia, M. D., Addabbo, M., Nava, E., Croci, E., Girelli, L., & Macchi Cassia, V. (2017). Infants' detection of increasing numerical order comes before detection of decreasing number. *Cognition*, 158, 177–188. <https://doi.org/10.1016/j.cognition.2016.10.022>
- de Hevia, M. D., Girelli, L., Addabbo, M., & Macchi Cassia, V. (2014). Human Infants' Preference for Left-to-Right Oriented Increasing Numerical Sequences. *PLoS ONE*, 9(5), e96412. <https://doi.org/10.1371/journal.pone.0096412>
- de Hevia, M. D., Girelli, L., Bricolo, E., & Vallar, G. (2008). The representational space of numerical magnitude: Illusions of length. *Quarterly Journal of Experimental Psychology*, 61(10), 1496–1514. <https://doi.org/10.1080/17470210701560674>
- de Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2012). Minds without language represent number through space: Origins of the mental number line. *Frontiers in Psychology*, 3. <https://doi.org/10.3389/fpsyg.2012.00466>
- de Hevia, M. D., Girelli, L., & Vallar, G. (2006). Numbers and space: A cognitive illusion? *Experimental Brain Research*, 168(1–2), 254–264. <https://doi.org/10.1007/s00221-005-0084-0>
- de Hevia, M. D., Izard, V., Coubart, A., Spelke, E. S., & Streri, A. (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences*, 111(13), 4809–4813. <https://doi.org/10.1073/pnas.1323628111>
- de Hevia, M. D., & Spelke, E. S. (2009). Spontaneous mapping of number and space in adults and young children. *Cognition*, 110(2), 198–207. <https://doi.org/10.1016/j.cognition.2008.11.003>
- de Hevia, M. D., & Spelke, E. S. (2010). Number-Space Mapping in Human Infants. *Psychological Science*, 21(5), 653–660. <https://doi.org/10.1177/0956797610366091>
- de Hevia, M. D., & Spelke, E. S. (2013). Not All Continuous Dimensions Map Equally: Number-Brightness Mapping in Human Infants. *PLoS ONE*, 8(11), e81241. <https://doi.org/10.1371/journal.pone.0081241>
- de Hevia, M. D., Vanderslice, M., & Spelke, E. S. (2012). Cross-Dimensional Mapping of Number, Length and Brightness by Preschool Children. *PLoS ONE*, 7(4), e35530. <https://doi.org/10.1371/journal.pone.0035530>
- de Hevia, M. D., Veggiotti, L., Streri, A., & Bonn, C. D. (2017). At Birth, Humans Associate “Few” with Left and “Many” with Right. *Current Biology*, 27(24), 3879–3884.e2. <https://doi.org/10.1016/j.cub.2017.11.024>
- de Schonen, S., & Mathivet, E. (1990). Hemispheric asymmetry in a face discrimination task in infants. *Child Development*, 61(4), 1192–1205.
- Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, 44(1–2), 1–42. [https://doi.org/10.1016/0010-0277\(92\)90049-N](https://doi.org/10.1016/0010-0277(92)90049-N)
- Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, 122(3), 371. <https://doi.org/10.1037/0096-3445.122.3.371>
- Dehaene, S., Izard, V., Spelke, E., & Pica, P. (2008). Log or Linear? Distinct Intuitions of the Number Scale in Western and Amazonian Indigenous Cultures. *Science*, 320(5880), 1217–1220. <https://doi.org/10.1126/science.1156540>
- Deruelle, C., & de Schonen, S. (1995). Pattern processing in infancy: Hemispheric differences in the processing of shape and location of visual components. *Infant Behavior and Development*, 18(2), 123–132.
- Deruelle, C., & de Schonen, S. (1998). Do the right and left hemispheres attend to the same visuospatial information within a face in infancy? *Developmental Neuropsychology*, 14(4), 535–554.
- Di Giorgio, E., Lunghi, M., Rugani, R., Regolin, L., Dalla Barba, B., Vallortigara, G., & Simion, F. (2019). A mental number line in human newborns. *Developmental Science*, 22(6), e12801.
- Di Luca, S., Granà, A., Semenza, C., Seron, X., & Pesenti, M. (2006). Finger–digit compatibility in Arabic numeral processing. *Quarterly Journal of Experimental Psychology*, 59(9), 1648–1663.
- Dodd, M. D., Stigchel, S. V. der, Adil Leghari, M., Fung, G., & Kingstone, A. (2008). Attentional SNARC: There's something special about numbers (let us count the ways). *Cognition*, 108(3), 810–818. <https://doi.org/10.1016/j.cognition.2008.04.006>
- Dolscheid, S., Hunnius, S., Casasanto, D., & Majid, A. (2014). Prelinguistic infants are sensitive to space-pitch associations found across cultures. *Psychological Science*, 25(6), 1256–1261.
- Drucker, C. B., & Brannon, E. M. (2014). Rhesus monkeys (*Macaca mulatta*) map number onto space. *Cognition*, 132(1), 57–67.
- Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology*, 43(6), 1428–1446. <https://doi.org/10.1037/0012-1649.43.6.1428>
- Felisatti, A., Laubrock, J., Shaki, S., & Fischer, M. H. (2020). A biological foundation for spatial–numerical associations: The brain's asymmetric frequency tuning. *Annals of the New York Academy of Sciences*, 1477(1), 44–53.
- Fernández-Prieto, I., Navarra, J., & Pons, F. (2015). How big is this sound? Crossmodal association between pitch and size in infants. *Infant Behavior and Development*, 38, 77–81.
- Fias, W. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. *Mathematical Cognition*, 2(1), 95–110.
- Fischer, M. H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex*, 44(4), 386–392.

- Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience*, 6(6), 555–556.
- Gentner, D., & Markman, A. B. (2006). Defining structural similarity. *The Journal of Cognitive Science*, 6(1), 1–20.
- Gervain, J., Abboub, N., & de Hevia, M. D. (2020). *The discrimination of numerosities by newborn infants: An fNIRS study*. International Conference on Infant Studies.
- Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representation of ordinal sequences is spatially organized. *Cognition*, 87(3), B87–B95.
- Gevers, W., Reynvoet, B., & Fias, W. (2004). The mental representation of ordinal sequences is spatially organised: Evidence from days of the week. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior*.
- Girelli, L., Lucangeli, D., & Butterworth, B. (2000). The development of automaticity in accessing number magnitude. *Journal of Experimental Child Psychology*, 76(2), 104–122.
- Guida, A., Fartoukh, M., & Mathy, F. (2020). The development of working memory spatialization revealed by using the cave paradigm in a two-alternative spatial choice. *Annals of the New York Academy of Sciences*, 1477(1), 54–70. <https://doi.org/10.1111/nyas.14433>
- Guida, A., Megreya, A. M., Lavielle-Guida, M., Noël, Y., Mathy, F., van Dijck, J.-P., & Abrahamse, E. (2018). Spatialization in working memory is related to literacy and reading direction: Culture “literarily” directs our thoughts. *Cognition*, 175, 96–100.
- Halberda, J., Ly, R., Wilmer, J. B., Naiman, D. Q., & Germine, L. (2012). Number sense across the lifespan as revealed by a massive Internet-based sample. *Proceedings of the National Academy of Sciences*, 109(28), 11116–11120. <https://doi.org/10.1073/pnas.1200196109>
- Harvey, B. M., Fracasso, A., Petridou, N., & Dumoulin, S. O. (2015). Topographic representations of object size and relationships with numerosity reveal generalized quantity processing in human parietal cortex. *Proceedings of the National Academy of Sciences*, 112(44), 13525–13530.
- Hurewitz, F., Gelman, R., & Schnitzer, B. (2006). Sometimes area counts more than number. *Proceedings of the National Academy of Sciences*, 103(51), 19599–19604.
- Hyde, D. C., Boas, D. A., Blair, C., & Carey, S. (2010). Near-infrared spectroscopy shows right parietal specialization for number in pre-verbal infants. *Neuroimage*, 53(2), 647–652.
- Ishihara, M., Keller, P. E., Rossetti, Y., & Prinz, W. (2008). Horizontal spatial representations of time: Evidence for the STEARC effect. *Cortex*, 44(4), 454–461.
- Izard, V., Dehaene-Lambertz, G., & Dehaene, S. (2008). Distinct cerebral pathways for object identity and number in human infants. *PLoS Biology*, 6(2), e11.
- Izard, V., Sann, C., Spelke, E. S., & Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences*, 106(25), 10382–10385.
- Johnson, S. P., Fernandes, K. J., Frank, M. C., Kirkham, N., Marcus, G., Rabagliati, H., & Slemmer, J. A. (2009). Abstract Rule Learning for Visual Sequences in 8- and 11-Month-Olds. *Infancy*, 14(1), 2–18. <https://doi.org/10.1080/15250000802569611>
- Kinsbourne, M. (1970). The cerebral basis of lateral asymmetries in attention. *Acta Psychologica*, 33, 193–201.
- Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition*, 83(2), B35–B42.
- Knops, A., Thirion, B., Hubbard, E. M., Michel, V., & Dehaene, S. (2009). Recruitment of an Area Involved in Eye Movements During Mental Arithmetic. *Science*, 324(5934), 1583–1585. <https://doi.org/10.1126/science.1171599>
- Lakoff, G., & Núñez, R. (2000). *Where mathematics comes from* (Vol. 6). New York: Basic Books.
- Lewkowicz, D. J., & Turkewitz, G. (1980). Cross-modal equivalence in early infancy: Auditory–visual intensity matching. *Developmental Psychology*, 16(6), 597.
- Lipton, J. S., & Spelke, E. S. (2004). Discrimination of large and small numerosities by human infants. *Infancy*, 5(3), 271–290.
- Liu, S., Brooks, N. B., & Spelke, E. S. (2019). Origins of the concepts cause, cost, and goal in prereaching infants. *Proceedings of the National Academy of Sciences*, 116(36), 17747–17752.
- Liu, S., Ullman, T. D., Tenenbaum, J. B., & Spelke, E. S. (2017). Ten-month-old infants infer the value of goals from the costs of actions. *Science*, 358(6366), 1038–1041.
- Lourenco, S. F., & Longo, M. R. (2010). General magnitude representation in human infants. *Psychological Science*, 21(6), 873–881.
- Macchi Cassia, V., Bulf, H., McCrink, K., & De Hevia, M. D. (2017). *Operational momentum during ordering operations for size and number in 4-month-old infants*. <https://doi.org/10.23668/PSYCHARCHIVES.1461>
- Macchi Cassia, V., McCrink, K., de Hevia, M. D., Gariboldi, V., & Bulf, H. (2016). Operational momentum and size ordering in preverbal infants. *Psychological Research*, 80(3), 360–367. <https://doi.org/10.1007/s00426-016-0750-9>
- Macchi Cassia, V., Picozzi, M., Girelli, L., & de Hevia, M. D. (2012). Increasing magnitude counts more: Asymmetrical processing of ordinality in 4-month-old infants. *Cognition*, 124(2), 183–193. <https://doi.org/10.1016/j.cognition.2012.05.004>

- Masson, N., Andres, M., Alsamour, M., Bollen, Z., & Pesenti, M. (2020). Spatial biases in mental arithmetic are independent of reading/writing habits: Evidence from French and Arabic speakers. *Cognition*, *200*, 104262. <https://doi.org/10.1016/j.cognition.2020.104262>
- McCrink, K., Caldera, C., & Shaki, S. (2018). The Early Construction of Spatial Attention: Culture, Space, and Gesture in Parent-Child Interactions. *Child Development*, *89*(4), 1141–1156. <https://doi.org/10.1111/cdev.12781>
- McCrink, K., & de Hevia, M. D. (2018). From Innate Spatial Biases to Enculturated Spatial Cognition: The Case of Spatial Associations in Number and Other Sequences. *Frontiers in Psychology*, *9*, 415. <https://doi.org/10.3389/fpsyg.2018.00415>
- McCrink, K., Dehaene, S., & Dehaene-Lambertz, G. (2007). Moving along the number line: Operational momentum in nonsymbolic arithmetic. *Perception & Psychophysics*, *69*(8), 1324–1333.
- McCrink, K., & Shaki, S. (2016). Culturally inconsistent spatial structure reduces learning. *Acta Psychologica*, *169*, 20–26.
- McCrink, K., Veggiotti, L., & de Hevia, M. D. (2020). A left visual advantage for quantity processing in neonates. *Annals of the New York Academy of Sciences*.
- McCrink, K., & Wynn, K. (2009). Operational momentum in large-number addition and subtraction by 9-month-olds. *Journal of Experimental Child Psychology*, *103*(4), 400–408.
- Náñez, José. (1988). Perception of impending collision in 3-to 6-week-old human infants. *Infant Behavior and Development*, *11*(4), 447–463. [https://doi.org/10.1016/0163-6383\(88\)90005-7](https://doi.org/10.1016/0163-6383(88)90005-7)
- Nava, E., de Hevia, M. D., Bulf, H., & Cassia, V. M. (2022). Signatures of functional visuospatial asymmetries in early infancy. *Journal of Experimental Child Psychology*, *215*, 105326.
- Newcombe, N., & Huttenlocher, J. (2003). *Making space: The development of spatial representation and reasoning*. MIT Press.
- Noël, M.-P. (2005). Finger gnosia: A predictor of numerical abilities in children? *Child Neuropsychology*, *11*(5), 413–430.
- Odic, D. (2018). Children's intuitive sense of number develops independently of their perception of area, density, length, and time. *Developmental Science*, *21*(2), e12533.
- Ouellet, M., Santiago, J., Israeli, Z., & Gabay, S. (2010). Is the future the right time? *Experimental Psychology*.
- Patro, K., & Haman, M. (2012). The spatial-numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology*, *111*(3), 534–542.
- Patro, K., & Haman, M. (2017). Playing Reading, Using Hands: Which Activities are Linked to Number-Space Processing in Preschool Children? *Psychology of Language and Communication*, *21*(1), 325.
- Piantadosi, S. T., & Cantlon, J. F. (2017). True Numerical Cognition in the Wild. *Psychological Science*, *28*(4), 462–469. <https://doi.org/10.1177/0956797616686862>
- Picozzi, M., de Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2010). Seven-month-olds detect ordinal numerical relationships within temporal sequences. *Journal of Experimental Child Psychology*, *107*(3), 359–367. <https://doi.org/10.1016/j.jecp.2010.05.005>
- Pitt, B., & Casasanto, D. (2020). The correlations in experience principle: How culture shapes concepts of time and number. *Journal of Experimental Psychology: General*, *149*(6), 1048.
- Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. <https://doi.org/10.1080/00335558008248231>
- Previtali, P., de Hevia, M. D., & Girelli, L. (2010). Placing order in space: The SNARC effect in serial learning. *Experimental Brain Research*, *201*(3), 599–605. <https://doi.org/10.1007/s00221-009-2063-3>
- Ranzini, M., Scarpazza, C., Radua, J., Cutini, S., Semenza, C., & Zorzi, M. (2022). A common neural substrate for number comparison, hand reaching and grasping: A SDM-PSI meta-analysis of neuroimaging studies. *Cortex*.
- Ren, P., Nicholls, M. E., Ma, Y., & Chen, L. (2011). Size matters: Non-numerical magnitude affects the spatial coding of response. *PLoS One*, *6*(8), e23553.
- Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology*, *83*(2p1), 274.
- Rinaldi, L., Di Luca, S., Toneatto, C., & Girelli, L. (2020). The effects of hemispheric dominance, literacy acquisition, and handedness on the development of visuospatial attention: A study in preschoolers and second graders. *Journal of Experimental Child Psychology*, *195*, 104830.
- Rugani, R., & de Hevia, M.-D. (2017). Number-space associations without language: Evidence from preverbal human infants and non-human animal species. *Psychonomic Bulletin & Review*, *24*(2), 352–369. <https://doi.org/10.3758/s13423-016-1126-2>
- Rugani, R., Kelly, D. M., Szelest, I., Regolin, L., & Vallortigara, G. (2010). Is it only humans that count from left to right? *Biology Letters*, *6*(3), 290–292.
- Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science*, *347*(6221), 534–536.
- Rusconi, E., Kwan, B., Giordano, B., Umiltà, C., & Butterworth, B. (2006). Spatial representation of pitch height: The SMARC effect. *Cognition*, *99*(2), 113–129. <https://doi.org/10.1016/j.cognition.2005.01.004>
- Santiago, J., Lupáñez, J., Pérez, E., & Funes, M. J. (2007). Time (also) flies from left to right. *Psychonomic Bulletin &*

- Review*, 14(3), 512–516. <https://doi.org/10.3758/BF03194099>
- Santiago, J., Román, A., Ouellet, M., Rodríguez, N., & Pérez-Azor, P. (2010). In hindsight, life flows from left to right. *Psychological Research Psychologische Forschung*, 74(1), 59–70. <https://doi.org/10.1007/s00426-008-0220-0>
- Scholl, B. J. (2001). Objects and attention: The state of the art. *Cognition*, 80(1–2), 1–46.
- Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review*, 16(2), 328–331.
- Skerry, A. E., Carey, S. E., & Spelke, E. S. (2013). First-person action experience reveals sensitivity to action efficiency in prereaching infants. *Proceedings of the National Academy of Sciences*, 110(46), 18728–18733.
- Skerry, A. E., & Spelke, E. S. (2014). Preverbal infants identify emotional reactions that are incongruent with goal outcomes. *Cognition*, 130(2), 204–216.
- Srinivasan, M., & Carey, S. (2010). The long and the short of it: On the nature and origin of functional overlap between representations of space and time. *Cognition*, 116(2), 217–241.
- Stevens, J. C., & Marks, L. E. (1965). Cross-modality matching of brightness and loudness. *Proceedings of the National Academy of Sciences of the United States of America*, 54(2), 407.
- Stevens, S. S. (1957). On the psychophysical law. *Psychological Review*, 64(3), 153.
- Tillman, K. A., Tulagan, N., Fukuda, E., & Barner, D. (2018). The mental timeline is gradually constructed in childhood. *Developmental Science*, 21(6), e12679.
- Tversky, B. (2014). Visualizing thought. In *Handbook of human centric visualization* (pp. 3–40). Springer.
- Vallortigara, G. (2018). Comparative cognition of number and space: The case of geometry and of the mental number line. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 373(1740), 20170120.
- van't Noordende, J. E., Volman, M. (Chiel) J., Leseman, P. P., & Kroesbergen, E. H. (2017). An Embodiment Perspective on Number–Space Mapping in 3.5-Year-Old Dutch Children. *Infant and Child Development*, 26(3), e1995.
- Viarouge, A., & de Hevia, M. D. (2013). The role of numerical magnitude and order in the illusory perception of size and brightness. *Frontiers in Psychology*, 4. <https://doi.org/10.3389/fpsyg.2013.00484>
- Walker, P., Bremner, J. G., Mason, U., Spring, J., Mattock, K., Slater, A., & Johnson, S. P. (2010). Preverbal infants' sensitivity to synaesthetic cross-modality correspondences. *Psychological Science*, 21(1), 21–25.
- Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, 7(11), 483–488.
- Wang, J., & Feigenson, L. (2021). Dynamic changes in numerical acuity in 4-month-old infants. *Infancy*, 26(1), 47–62.
- Wilcox, T., Haslup, J. A., & Boas, D. A. (2010). Dissociation of processing of featural and spatiotemporal information in the infant cortex. *Neuroimage*, 53(4), 1256–1263.
- Wood, J. N., Glynn, D. D., Phillips, B. C., & Hauser, M. D. (2007). The perception of rational, goal-directed action in nonhuman primates. *Science*, 317(5843), 1402–1405.
- Wood, J. N., & Spelke, E. S. (2005). Chronometric studies of numerical cognition in five-month-old infants. *Cognition*, 97(1), 23–39.
- Woodward, A. L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition*, 69(1), 1–34.
- Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, 74(1), B1–B11.
- Zebian, S. (2005). Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture*, 5(1–2), 165–190.
- Zorzi, M., Priftis, K., & Umiltà, C. (2002). Neglect disrupts the mental number line. *Nature*, 417(6885), 138–139.

## Annex 1: Journals rankings

***Annals of the New York Academy of Sciences*** (1 publication)

IF: 5.69; Q1 (Multidisciplinary Sciences).

***Behavioral and Brain Sciences*** (1 publication)

IF: 12.58; Q1 (Neurosciences; Behavioral Sciences).

***Behavioral Sciences*** (1 publication)

IF: 2.66; Q1 (Psychology; Multidisciplinary).

***Child Development Perspectives*** (1 publication)

IF: 6.22; Q1 (Psychology; Developmental).

***Cognition*** (6 publications)

IF: 3.65; Q1 (Psychology; Experimental).

***Cortex*** (1 publication)

IF: 4.03; Q1 (Psychology; Experimental; Neurosciences; Behavioral Sciences).

***Current Biology*** (1 publication)

IF: 10.83; Q1 (Biology).

***Developmental Science*** (1 publication)

IF: 5.13; Q1 (Psychology, Experimental; Psychology, Developmental).

***Experimental Brain Research*** (3 publications)

IF: 1.97; Q3 (Neurosciences).

***Experimental Psychology*** (2 publications)

IF: 1.19; Q2 (Psychology; Experimental).

***Frontiers in Human Neuroscience*** (1 publication)

IF: 3.17; Q2 (Neurosciences; Psychology).

***Frontiers in Psychology*** (3 publications)

IF: 2.99; Q2 (Psychology; Multidisciplinary).

***Functional Neurology*** (1 publication)

IF: 1.43; Q3 (Clinical Neurology).

***Journal of Experimental Child Psychology*** (3 publications)

IF: 2.61; Q1 (Psychology, Experimental; Psychology, Developmental).

***Journal of Numerical Cognition*** (1 publication)

IF: 0.86; Q3 (Experimental and Cognitive Psychology).

***Neuroscience & Biobehavioral Reviews*** (1 publication)

IF: 8.99; Q1 (Neurosciences; Behavioral Sciences).

***PLOS One*** (6 publications)  
IF: 3.24; Q2 (Multidisciplinary Sciences).

***Proceedings of the National Academy of Sciences of the United States of America*** (1 publication)  
IF: 10.7; Q1 (Multidisciplinary Sciences).

***Progress in Brain Research*** (1 publication)  
IF: 2.49; Q2 (Neurosciences).

***Psychonomic Bulletin & Review*** (1 publication)  
IF: 5.54; Q1 (Psychology; Experimental).

***Psychological Research*** (1 publication)  
IF: 2.96; Q2 (Psychology; Experimental).

***Psychological Science*** (1 publication)  
IF: 7.03; Q1 (Psychology; Multidisciplinary).

***Quarterly Journal of Experimental Psychology*** (1 publication)  
IF: 2.14; Q1 (Experimental and Cognitive Psychology).

***Scientific Reports*** (3 publications)  
IF: 4.38; Q1 (Multidisciplinary Sciences).

***Timing & Time Perception Reviews*** (1 publication)  
IF: 1.48; Q2 (Experimental and Cognitive Psychology).