

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <https://orca.cardiff.ac.uk/id/eprint/127376/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Tecwyn, Emma C. , Bechlivanidis, Christos, Lagnado, David A., Hoerl, Christoph, Lorimer, Sara, Blakey, Emma, McCormack, Teresa and Buehner, Marc J. 2020. Causality influences children's and adults' experience of temporal order. *Developmental Psychology* 56 (4) , pp. 739-755. 10.1037/dev0000889

Publishers page: <http://doi.org/10.1037/dev0000889>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

Causality Influences Children’s and Adults’ Experience of Temporal Order

Running Title: Development of Causal Reordering

Emma C Tecwyn ^{1*}, Christos Bechlivanidis ², David A Lagnado ², Christoph Hoerl ³, Sara Lorimer ⁴, Emma Blakey ⁵, Teresa McCormack ⁴, & Marc J Buehner ¹

1 Cardiff University, School of Psychology

2 University College London, Department of Psychology

3 University of Warwick, Department of Philosophy

4 Queen’s University Belfast, School of Psychology

5 The University of Sheffield, Department of Psychology

Author note

This research was funded by Leverhulme Trust Research Project Grant RPG-2015-267

* Correspondence: emma.tecwyn@bcu.ac.uk

Emma C Tecwyn is now at Department of Psychology, Birmingham City University

The authors have no conflict of interest to declare.

26

Abstract

27 Although it has long been known that time is a cue to causation, recent work with adults has
28 demonstrated that causality can also influence the experience of time. In *causal reordering*
29 (Bechlivanidis & Lagnado, 2013, 2016) adults tend to report the causally consistent order of
30 events, rather than the correct temporal order. However, the effect has yet to be demonstrated
31 in children. Across four pre-registered experiments, 4- to 10-year-old children (N=813) and
32 adults (N=178) watched a 3-object Michotte-style ‘pseudocollision’. While in the canonical
33 version of the clip object A collided with B, which then collided with object C (order: ABC),
34 the pseudocollision involved the same spatial array of objects but featured object C moving
35 before object B (order: ACB), with no collision between B and C. Participants were asked to
36 judge the temporal order of events and whether object B collided with C. Across all age
37 groups, participants were significantly more likely to judge that B collided with C in the 3-
38 object pseudocollision than in a 2-object control clip (where clear causal direction was
39 lacking), despite the spatiotemporal relations between B and C being identical in the two
40 clips (Experiments 1–3). Collision judgements and temporal order judgements were not
41 entirely consistent, with some participants—particularly in the younger age range—basing
42 their temporal order judgements on spatial rather than temporal information (Experiment 4).
43 We conclude that in both children and adults, rather than causal impressions being
44 determined only by the basic spatial-temporal properties of object movement, schemata are
45 used in a top-down manner when interpreting perceptual displays.

46

47 *Keywords:* causality, causal perception, cognitive development, Michottean launching,
48 temporal cognition, time perception

49

Causality Influences Children's and Adults' Experience of Temporal Order

The ability to learn about and represent causal relations is fundamental to our ability to navigate and understand the world as it enables us to interpret, explain and thus predict, events in our environment. A large body of research suggests that from a young age, children represent causal structures and use this information to guide their inferences and behaviour (see Muentener & Bonawitz, 2017; Sobel & Legare, 2014 for recent reviews). There is evidence that causal knowledge contributes to the development of children's cognitive skills in a variety of domains (e.g., physical reasoning, Baillargeon, 2004; moral reasoning, Hamlin, 2013; generating explanations, Legare, 2012), thus demonstrating that causality plays a central role in our experience of the world from early in life.

It has long been known that temporal cues strongly influence people's causal judgements. Both adults' (e.g., Buehner & May, 2003; Lagnado & Sloman, 2006) and children's (e.g., Bullock & Gelman, 1979; McCormack et al., 2015; Mendelson & Shultz, 1976; Rankin & McCormack, 2013; Schlottmann et al., 1999) causal judgements show sensitivity to the principles of temporal priority (causes must precede their effects) and temporal contiguity (causally related events typically occur close together in time). More recently, it has become apparent that the relations between time and causality are in fact bidirectional—just as temporal cues influence our causal judgements, causal beliefs, in turn, influence the experience of time. Empirically, this influence of causal beliefs on temporal experience has been demonstrated in studies of two effects: *causal binding* and *causal reordering*. Studies of causal binding have shown that if one event A is believed to be the cause of another event B, the interval between the two events is perceived as shorter in duration than the same objective interval where the two events are not causally linked (Buehner 2012; 2015; Buehner & Humphreys, 2009). This represents a quantitative shift in

74 the perception of the temporal duration of an interval, such that causally-related events are
75 drawn towards one another, or ‘bound’ together in time.

76 A small number of recent studies have also demonstrated that causal beliefs can
77 influence not only the subjective interval between events but also the temporal order in which
78 the events are perceived to occur. In causal reordering (Bechlivanidis & Lagnado, 2013;
79 2016) the temporal order in which events are perceived to have occurred is reversed, so that
80 the experienced order of events is in line with causality. That is, if participants have a
81 background belief that A is a cause of B, they are likely to report that A happened before B
82 even when shown a sequence of events in which B happened first. In the first study to
83 demonstrate causal reordering, participants interacted with an on-screen ‘physics world’
84 consisting of animated objects with different properties. After learning the properties of the
85 objects and the causal relations between them, participants watched a clip that violated the
86 learned causal order of events (i.e., if they had learned that A caused B, they saw a clip in
87 which B happened before A). Participants were significantly more likely to report that events
88 occurred in the order consistent with their causal beliefs than the objective temporal order
89 (Bechlivanidis & Lagnado, 2013).

90 Further evidence that causal beliefs influence adults’ experience of the temporal order
91 of events comes from a study by Desantis and colleagues (2016). In this study participants
92 watched a random-dot-kinematogram (RDK) on a computer screen and learned that pressing
93 one key (e.g., left) caused the RDK motion to become briefly coherent in one direction (e.g.,
94 upwards), and pressing a different key (e.g., right) led to coherent motion in the opposite
95 direction (e.g., downwards). Having learned this association, in a critical test phase,
96 participants continued to execute keypresses, but sometimes the coherent motion of the RDK
97 occurred *before* the keypress. For these trials, participants were more likely to (incorrectly)
98 report that the motion occurred after their keypress when coherent motion was in the

99 expected (i.e. learnt) direction, compared with when it was in the unexpected, incongruent
100 direction. This finding is indicative of causal reordering because participants apparently
101 perceived events to occur in the order that reflected their learned causal beliefs (Desantis et
102 al., 2016).

103 The above causal reordering studies were based on causal relations that participants
104 learned in an initial training phase. On the basis of this evidence alone, it is not possible to
105 determine whether the reordering effect is dependent on recently learned rules about
106 unfamiliar causes and effects, or whether it might represent a more general phenomenon that
107 occurs in any situation that evokes an impression of causality. In addition, the Desantis et al.
108 (2016) study involved intentional action by the participant, thus the reordering effect found
109 might not be explained solely by causal beliefs (e.g., illusion of control could also play a
110 role). To address these issues, Bechlivanidis and Lagnado (2016) designed a ‘one shot’
111 experiment that involved showing participants a single brief clip. The clip was based on a
112 Michottean launching event (i.e. a simple collision between horizontally arranged two-
113 dimensional objects), adapted to involve three objects (ABC) instead of the typical two.
114 Crucially, the third object in line (C) moved before the second object in line (B); i.e., the
115 effect occurred *before* its presumed cause (see e.g., Figure 2a). Participants were significantly
116 more likely to report perceiving that the events happened in an order consistent with
117 causation (ABC) than in the objective temporal order (ACB). Participants also tended to
118 (incorrectly) report that B made C move, suggesting that presumed causality—in the form of
119 a collision between B and C—was the basis on which reordering occurred (Bechlivanidis &
120 Lagnado, 2016).

121 Taken together, these studies provide compelling evidence that adults temporally
122 reorder events in line with their assumptions about causality, regardless of whether those
123 assumptions are the result of recent learning or are based on perceptual cues. However,

124 nothing is currently known about the developmental origins of this phenomenon, despite the
125 potential for developmental research to enhance our understanding of the nature of the links
126 between causal and temporal cognition. Children’s causal cognition has been studied
127 extensively (see Muentener & Bonawitz, 2017; Sobel & Legare, 2014 for recent reviews) and
128 even infants show some sensitivity to causality in Michottean launching displays (e.g., Leslie
129 & Keeble, 1987; Mascialzoni et al., 2013; Oakes, 1994; Schlottmann et al., 2002), but whether
130 children’s causal impressions are strong and reliable enough to modulate their temporal order
131 perception, as is true for adults, remains an open question.

132 Research on whether causal beliefs can affect children’s temporal perception has so
133 far been limited to a small number of developmental studies of causal binding—the perceived
134 shortening of duration between two events that are believed to be causally related. Cavazzana
135 and colleagues (2014, 2017) investigated the binding effect in 8- to 11-year-old children and
136 adults. In each trial, participants watched letters of the alphabet rapidly flash up on a screen in
137 a random order, and had to report which letter was on the screen when target events occurred.
138 In some trials participants heard two tones (which were causally unrelated to one another)
139 and in other trials participants pressed a key that resulted in a tone (causally related events),
140 with the duration between the pairs of events identical in both cases. The adults’ judgements
141 of which letters were on the screen when these target events occurred revealed the classic
142 binding effect—the causally related keypress and tone were perceived as occurring closer
143 together in time compared to the causally unrelated tones. However, the researchers failed to
144 find evidence of causal binding in the children, leading them to conclude that the effect
145 emerges late in development and may be linked to the development of higher-order cognitive
146 processes (Cavazzana, Begliomini, & Bisiacchi, 2014, 2017).

147 Although Cavazzana et al. concluded that this type of binding was a late-emerging
148 phenomenon, their findings contrast with those of some recent studies using simplified child-

149 friendly tasks. In these tasks, rather than retrospectively reporting the time at which an event
150 occurred, participants either anticipated when they expected a target event (e.g., a rocket on a
151 screen launching) to occur following an initial event (keypress or non-causal signal, Blakey et
152 al., 2018), or gave a categorical estimation of the interval between the two events (Lorimer et
153 al., under review). Children in both of these studies showed a binding effect—they were more
154 likely to perceive the duration between two events to be shorter when there was a causal
155 connection between them (i.e., when the rocket launch was caused by a keypress as opposed
156 to preceded by an arbitrary signal). These findings suggest that susceptibility to causal
157 binding is present in children as young as four years and that the magnitude of the binding
158 effect does not increase developmentally, even into adulthood (Blakey et al., 2018; Lorimer
159 et al., under review). Thus, it appears that, rather than being a late emerging phenomenon as
160 suggested by the results of Cavazanna et al., causal binding reflects a fundamental way in
161 which cognition shapes perception, and, at least from four years, is not modulated either by
162 increased experience of causal relations or higher-order cognitive/reasoning processes that
163 are known to change developmentally.

164 Causal binding and reordering effects are both examples of causal beliefs influencing
165 temporal experience, suggesting that the relationship between time and causality is
166 bidirectional. It thus seems intuitively plausible that the emergence of these effects may
167 follow the same developmental trajectory. However, it is difficult to generate developmental
168 predictions about causal reordering effects based on studies of causal binding, because there
169 are no detailed models of these effects that assume they have a common basis (indeed, there
170 is considerable disagreement over the mechanisms underpinning causal binding, e.g.,
171 Borhani, Beck, & Haggard, 2017; Buehner, 2012; Faro, McGill, & Hastie, 2013; Merchant &
172 Yarrow, 2016). Nevertheless, the recent studies on causal binding in children help motivate
173 an examination of whether causal reordering is also observable in children. The aim of the

197 Approval for this study (Experiments 1—4) was granted by Cardiff University School
198 of Psychology Ethics Committee, EC.16.02.09.4448R, ‘Time and Causality in Cognitive
199 Development’. All studies were pre-registered and are available at the following links:
200 Experiment 1: <https://osf.io/nqbtm/>, Experiment 2:
201 <https://osf.io/vcesk/register/565fb3678c5e4a66b5582f67>, Experiment 3:
202 <http://aspredicted.org/blind.php?x=z7e5xr>; Experiment 4:
203 <http://aspredicted.org/blind.php?x=ip226r>.

204 **Participants**

205 For each experiment we initially aimed to recruit approximately 30 participants per
206 age group and use a within-subjects design (for the sake of economic use of participants),
207 with participants viewing both of the critical clips (there were two in each experiment, the 3-
208 object pseudocollision and the control clip) in a counterbalanced order, yielding two
209 conditions (pseudocollision first or second). Once we reached this sample size we tested for
210 order effects; specifically, for each age group we tested whether the order in which
211 participants saw the two critical clips influenced their responses for either of our measures
212 (TOJ and CJ). For all four experiments, critical clip order influenced performance for at least
213 one age group on at least one measure (see supplementary Table S1 Figure S1); thus, in each
214 case we switched to a between-subjects design, whereby we proceeded to collect additional
215 data to give approximately 30 participants per age group per condition, and only analysed the
216 first of the two critical clips participants watched. That is, in the analyses reported below,
217 participants contributed data points for either the pseudocollision clip or the control clip.

218 The exact number of participants per experiment was determined by availability in
219 schools and museums. Specifically, we did not turn away anyone who wanted to participate
220 while we were in a given setting. To enable us to examine performance differences across

221 development and compare children and adults within the same model the child sample for
222 each experiment was divided into multiple age groups.

223 All participants were tested individually. Adults were either tested in a room at a
224 university (undergraduate students) or at a local science museum (museum visitors). The
225 adults tested at a university received course credit for participating. Children were either
226 tested in a room at their school or at a local science museum and received a sticker for
227 participating.

228 **Materials**

229 All experiments were programmed in Adobe Flex 4.6 and presented to participants on
230 an Acer TravelMate P236 13.3” laptop. Examples of the clips presented in Experiment 1 are
231 depicted in Figures 1 and 2.

232 **Design**

233 All Participants only took part in one of the four experiments. The following variables
234 were randomized across participants: direction of object motion in clips (left to right, right to
235 left); practice clip order; colour of the shapes (which varied between experiments).

236 **Coding and preliminary analyses**

237 For each critical clip we coded participants’ responses to (a) the TOJ question (shape
238 selected (A, B, C) and whether it was correct/incorrect) and (b) the CJ question (yes/no and
239 whether it was correct/incorrect). For each experiment we ran preliminary analyses to check
240 for an effect of direction of motion (left-right or right-left) on either of our response variables.
241 As we found no significant influence of motion direction, data were collapsed across this
242 variable for all subsequent analyses.

243 **Experiment 1**

244 In Experiment 1, we modified Bechlivanidis and Lagnado’s (2016) Experiment 1 to
245 make it more appropriate for young children. The critical clips were identical in terms of their
246 spatiotemporal features to those used in the original study. However, whereas participants in
247 Bechlivanidis and Lagnado’s (2016) experiment were required to order all of the events that
248 occurred via drag and drop, we greatly simplified the response variables to reduce task
249 demands. In the critical clips for our task, participants were asked a single temporal order
250 judgement (TOJ) question (“Which square started moving last?”) and a single collision
251 judgement (CJ) question (“Did square B bump into square C, yes or no?” see Method for
252 further details). We also introduced 4 non-causal practice clips (two involving two objects
253 and two involving three objects; Figure 1a—b) that participants watched before viewing the
254 critical clips, to familiarize participants with the type of clip they would be watching and
255 what they should be attending to.

256 **Method**

257 **Participants.** Our final sample consisted of 61 adults (41 female, 3-object: $N = 31$,
258 $M_{age} = 29$ years; 2-object: $N = 30$, $M_{age} = 23$ years) and 282 children (164 female). An
259 additional four children were tested but excluded because they were inattentive ($N = 3$) or did
260 not understand the task instructions ($N = 1$). The child sample was divided into 4 age groups
261 per condition: 4- to 6-year-olds (3-object: $N = 35$, $M_{age} = 5$ years 8 months; 2-object: $N = 35$,
262 $M_{age} = 5$ years 4 months), 6- to 7-year-olds (3-object: $N = 36$, $M_{age} = 7$ years 2 months; 2-
263 object: $N = 35$, $M_{age} = 7$ years 0 months), 7- to 9-year-olds (3-object: $N = 35$, $M_{age} = 8$ years 8
264 months; 2-object: $N = 35$, $M_{age} = 8$ years 5 months) and 9- to 10-year-olds (3-object: $N = 36$,
265 $M_{age} = 9$ years 11 months; 2-object: $N = 35$, $M_{age} = 9$ years 9 months).

266 **Procedure.** Participants were told that they would watch some short clips of squares
267 moving around on the screen and answer some questions about what they saw. They were

290 pseudocollision (Figure 2a), square A moved towards square B and stopped adjacent to it;
291 immediately after this, square C started moving away from square B, and after 350 ms,
292 square B started moving away from square A; at no stage did square B make contact with
293 square C. All shapes moved at a speed of 30 mm/s. The 2-object control clip was identical to
294 the 3-object pseudocollision, except that square A was not present (Figure 2b). Critically, the
295 relative onset of motion of squares B and C was exactly the same in both clips.

296 As in the practice clips the shapes remained in their final positions after each critical
297 clip, and participants were asked a TOJ: “Which square started moving last?” This form of
298 words was used rather than the more straightforward “Which square moved last?” because
299 squares B and C stopped moving simultaneously (and so technically they both moved last).
300 Participants were also asked a collision judgement (CJ) question about shapes B and C: “Did
301 the (e.g.) black square (B) bump into the (e.g.) red square (C), yes or no?” and the
302 experimenter pointed at the relevant squares on the screen as they asked this question. The
303 aim of asking this was to establish whether children had the impression that B had collided
304 with C.

305 *Figure 2 about here*

306 **Pre-registered confirmatory analyses.** To establish which of the age groups tested
307 were susceptible to causal reordering, for each age group we used Chi-square tests to
308 compare participants’ TOJ and CJ responses in the 2-object control clip and the 3-object
309 pseudocollision (as a reminder, these clips were identical except for the inclusion/exclusion
310 of object A). Where the assumptions for using the chi-square test were not met (i.e., expected
311 values of < 5 in one or more cells) we used Fisher’s Exact Test. If participants were
312 reordering events in line with an impression of causality, we would expect a significantly

313 greater proportion of participants' TOJs and CJs to be accurate in the 2-object control clip
314 than in the 3-object pseudocollision.

315 **Exploratory analyses.** To further examine developmental changes in reordering we
316 used binomial logistic regression conducted in R (R Core Team, 2017) to ascertain the effect
317 of age group on the likelihood of responding correctly to (a) the TOJ question and (b) the CJ
318 question for the 3-object pseudocollision. If the models revealed a significant effect of age
319 group, planned pairwise comparisons were conducted with Tukey-adjusted p-values for
320 multiple comparisons, to establish which age groups differed from one another. Correlation
321 between our two measures (TOJs and CJs) was assessed by calculating Phi coefficients,
322 which is a measure of association between two binary variables. Specifically, we were
323 interested to know whether participants who reordered events B and C were more likely to
324 report perceiving a collision between these two objects (and vice versa).

325 **Results**

326 Following Bechlivanidis and Lagnado (2016) and our pre-registered analysis plan, for
327 the following analyses we excluded participants who, following the TOJ question, gave the
328 nonsensical response that square A started moving last. This resulted in the exclusion of
329 28/132 children (14 4- to 6-year-olds; seven 6- to 7-year-olds; six 7- to 9-year-olds; one 9- to
330 10-year-old) from the group who contributed data on the 3-object pseudocollision clip. No
331 adults needed to be excluded on this basis.

332 **Practice clips.** Performance in the 2-object practice clips ranged from 69% correct
333 responses (4- to 6-year-olds) to 93% correct responses (adults). Performance in the 3-object
334 practice clips ranged from 60% correct responses (4- to 6-year-olds) to 94% correct responses
335 (adults, see Table S2 for full details).

336 **Pre-registered confirmatory analyses.** Across all age groups, the majority of
337 participants responded correctly to the TOJ question (that B moved last) in the 2-object
338 control clip (Figure 3a). Participants in all age groups were significantly more likely to
339 respond correctly (say B started moving last) in the 2-object control clip than the 3-object
340 pseudocollision (Chi-square tests: $p < 0.001$ for all, Table 1). Participants in all age groups
341 were also significantly more likely to respond correctly (no) to the CJ question (e.g., “did the
342 green (B) square bump into the red (C) square, yes or no?”), see Figure 3b) in the 2-object
343 control clip than the 3-object pseudocollision (Chi-square tests: $p \leq 0.001$ for all, Table 1).

344 *Figure 3 about here*

345 *Table 1 about here*

346 **Exploratory analyses.** Logistic regression revealed that participants’ tendency to
347 report the correct order of events (TOJ question) in the pseudocollision was significantly
348 influenced by age group (Wald $\chi^2 = 10.68$, $df = 4$, $p = 0.030$). Posthoc contrasts with Tukey
349 adjusted p -values for multiple comparisons revealed a significant difference between adults
350 and 9- to 10-year-olds (log odds ratio = 1.54, $p = 0.036$), with adults being more likely to
351 respond correctly/less likely to reorder. There were no other significant differences between
352 groups after adjusting for multiple comparisons ($p \geq 0.124$ for all other pairs of age groups,
353 Table S3). Participants’ tendency to report perceiving a collision between objects B and C
354 (CJ question) in the pseudocollision was also significantly influenced by age group (Wald χ^2
355 = 10.43, $df = 4$, $p = 0.034$). Posthoc contrasts with Tukey adjusted p -values for multiple
356 comparisons revealed a significant difference between 9- to 10-year-olds and 7- to 9-year-
357 olds (log odds ratio = 1.72, $p = 0.038$), with the older children being more likely to perceive a
358 collision. There were no other significant differences between age groups in responses to the
359 CJ question after adjusting for multiple comparisons ($p \geq 0.470$ for all other pairwise

360 comparisons). These patterns of responding with age group as a categorical predictor were in
361 keeping with analyses of child data only when age in years was included as a continuous
362 predictor (see Table S6). TOJs and CJs were significantly associated for the 3-object
363 pseudocollision—participants who reordered events B and C were more likely to report
364 perceiving a collision between those objects ($\Phi = 0.26$, $p = 0.002$, see Table S7 for details
365 per age group).

366 **Discussion**

367 Across all of the age groups tested, participants were significantly more likely to
368 report the correct order of events (say that square B started moving last) in the 2-object
369 control clip than the 3-object pseudocollision clip, despite the relative onset of motion of
370 squares B and C being identical in both clips. The results for the 2-object clip provide
371 evidence that participants of all ages were able to perceptually distinguish the relative onset
372 of motion of squares B and C, as they almost always gave the correct response to the TOJ
373 question in this case. This suggests that participants' TOJs were influenced by the inclusion
374 of square A, which gave the clip clear causal direction. In addition, all participants were
375 significantly less likely to report perceiving contact between objects B and C in the 2-object
376 control clip than the 3-object pseudocollision (i.e., they were more likely to correctly respond
377 “no” to the CJ question in the former), which indicates that the causal impression generated
378 by the pseudocollision was the basis for reordering.

379 Adults in the present experiment were less likely to reorder than in Bechlivanidis and
380 Lagnado's (2016, Experiment 1) original one-shot study (42% vs. 83% reordering). This
381 difference in performance is probably due to the inclusion of practice trials in the present
382 task. Asking a TOJ question after each practice trial presumably causes participants to focus
383 more on the temporal order of events, so when they get to the critical clips they have a good

384 idea what they should be attending to. In fact, given the long temporal interval (350 ms)
385 between the motion of two objects and the fact that adults were expecting to be asked about
386 the temporal order of events, it is perhaps surprising that we nevertheless still find evidence
387 for reordering in almost half of the adults tested (in contrast, only 6% of adults responses
388 were incorrect in the 3-object practice trials). While 9- to -10-year-olds were more likely to
389 reorder events than adults in the 3-object pseudocollision, and more likely to report
390 perceiving a collision between objects B and C than 7- to 9-year-olds, there was no clear
391 developmental pattern in performance according to either of our measures.

392 Although the data from Experiment 1 provided some initial evidence that children as
393 young as four years reorder events in line with causal impressions, the fact that a large
394 proportion of participants in the younger age groups gave the response that object A started
395 moving last (41% in our youngest age group) and thus had to be excluded is unsatisfactory.
396 This high level of exclusions makes it impossible to properly determine the developmental
397 trajectory of the reordering phenomenon, as this hangs on how the A-responders would re-
398 distribute between B and C if they did not give the nonsensical A response. Why might
399 participants—specifically, young children—say that A started moving last? Two features of
400 Experiment 1 may have led children to respond in this way. First, while we deliberately
401 avoided the use of the terms “before” and “after” given young children’s well-established
402 difficulties with these terms, it is possible that the question “which square started moving
403 last?” is also rather complex for young children—particularly the combination of “started”
404 and “last”. Second, because we alternated the TOJ question between practice trials, either
405 asking which square moved first *or* which square moved last, it is possible that in some cases
406 children were expecting to be asked about which square moved first (rather than last) in the
407 critical clip, and gave a response to that question instead (though note that if this were true we
408 would expect the same issue to affect the 2-object control clip). In Experiment 2 we

409 addressed both these issues, with the aim of getting a clearer picture of the developmental
410 trajectory of susceptibility to causal reordering.

411 **Experiment 2**

412 In Experiment 2 we again presented participants with a 3-object pseudocollision and a
413 2-object control clip. However, to prevent participants from responding “A” in the critical
414 TOJ question, object A was a circle, whereas B and C were both squares, and we explicitly
415 asked about the squares (Figure 2a[ii]). Participants were introduced to the different shapes at
416 the start of the task, and they saw a practice clip involving a circle and two squares. To
417 address the other issues that might have contributed to the high levels of A-responding in
418 Experiment 1, we changed the TOJ so that for all clips (practice and critical) participants
419 were asked “Which square moved *first*?” We also reduced the number of practice clips from
420 four to two, as we suspected the extensive practice phase could have contributed to the
421 decreased prevalence of reordering in adults compared to the level reported by Bechlivanidis
422 and Lagnado (2016).

423 **Method**

424 **Participants.** Our final sample consisted of 63 adults (56 female; 3-object: N = 30,
425 M_{age} = 20 years; 2-object: N = 33, M_{age} = 20 years) and 207 children (127 female), none of
426 whom had participated in Experiment 1. An additional four children were tested but excluded
427 because of a lack of attention (N = 3) or insufficient English language skills (N = 1). The
428 child sample was divided into 3 age groups per condition: 4- to 6-year-olds (3-object: N = 33,
429 M_{age} = 5 years 5 months; 2-object: N = 32, M_{age} = 5 years 4 months), 6- to 8-year-olds (3-
430 object: N = 33, M_{age} = 7 years 4 months; 2-object: N = 32, M_{age} = 7 years 1 month) and 8- to
431 10-year-olds (3-object: N = 33, M_{age} = 9 years 8 months; 2-object: N = 32, M_{age} = 9 years 1
432 month).

433 **Materials.** The materials were the same as in Experiment 1 except that object A was a
434 circle and we changed the colour of the shapes to blue, orange and grey, as it occurred to us
435 that red-green colour-blindness could have been an issue in Experiment 1.

436 **Procedure.** The task instructions were the same as for Experiment 1, with the
437 addition that before viewing the practice clips participants were introduced to the different
438 shapes (square and circle), and children in the youngest age group were asked to name the
439 shapes (their data were excluded if they were unable to).

440 **Practice clips.** Participants watched two non-causal practice clips (Figure 1b) in a
441 random order and were asked the same TOJ question after each one: “Which square moved
442 first?”

443 **Critical clips.** The 2-object control clip was identical to the clip used in Experiment
444 1. The 3-object test clip was identical except that object A was a circle instead of a square
445 (Figure 2a[ii]).

446 **Results**

447 **Practice clips.** Performance in the 2-object practice clip ranged from 71% of
448 participants responding correctly (4- to 6-year-olds) to 87% of participants responding
449 correctly (adults). Performance in the 3-object practice clip ranged from 66% of participants
450 responding correctly (4- to 6-year-olds and 6- to 8-year-olds) to 90% of participants
451 responding correctly (adults, see Table S2 for full details).

452 **Pre-registered confirmatory analyses.** Across all age groups, the majority of
453 participants responded correctly to the TOJ question (that C moved first) in the 2-object
454 control clip (Figure 4a). In contrast to Experiment 1, in Experiment 2 there was a clear
455 pattern of decreasing response accuracy to the TOJ question for the 3-object pseudocollision
456 (blue bars of Figure 4a): younger children were more likely to respond correctly than older

457 children and adults when asked “Which square moved first?” Comparisons of TOJ responses
458 between the 2-object and 3-object clips revealed that while 8- to 10-year-olds and adults were
459 significantly more likely to respond correctly in the 2-object clip than the 3-object clip (chi-
460 square tests, $ps \leq 0.003$, Table 1), the 4- to 6- and 6- to 8-year-olds’ performance did not
461 differ significantly between the two critical clips (Fisher’s Exact Test, $ps > 0.082$).
462 Participants in all age groups were significantly more likely to say square B collided with
463 square C in the 3-object pseudocollision than the 2-object control clip (Figure 4b, Chi-square
464 tests: $ps \leq 0.002$ for all, Table 1).

465 *Figure 4 about here*

466
467 **Exploratory analyses.** Logistic regression revealed that participants’ tendency to
468 report the correct order of events (TOJ question) in the pseudocollision was significantly
469 influenced by age group (Wald $\chi^2 = 10.52$, $df = 3$, $p = 0.015$). After correcting p-values for
470 multiple comparisons (Tukey adjustment) the youngest children were significantly more
471 likely to respond correctly/less likely to reorder than adults (log odds ratio = 1.90, $p = 0.038$).
472 There were no other significant differences between groups after adjusting for multiple
473 comparisons ($p \geq 0.065$ for all other pairs of age groups, Table S4). Participants’ tendency to
474 report perceiving a collision between objects B and C (CJ question) in the 3-object
475 pseudocollision was not significantly influenced by age group (Wald $\chi^2 = 4.97$, $df = 3$, $p =$
476 0.172). These patterns of responding with age group as a categorical predictor were in
477 keeping with analyses of child data only when age in years was included as a continuous
478 predictor (see Table S6). TOJs and CJs were significantly associated for the 3-object
479 pseudocollision—participants who reordered events B and C were more likely to report
480 perceiving a collision between those objects (Phi = 0.19, $p = 0.029$, see Table S7 for details
481 per age group).

482 **Discussion**

483 Our Experiment 2 adult data closely replicates the results of Experiment 1—we again
484 found evidence for the reordering of events in line with causality, according to both the TOJ
485 data and the CJ data. Interestingly, reducing the number of practice clips appeared to have
486 little impact on adults’ susceptibility to reordering (we had speculated that including fewer
487 practice clips might lead to more adults reordering), though we did make additional task
488 modifications that could have reduced susceptibility (e.g., asking the same TOJ question
489 throughout; only ever asking about the squares). However, by contrast to the findings of
490 Experiment 1, children’s TOJs in Experiment 2 suggest that it is only from around 8 years of
491 age that reordering of events in line with causal impressions emerges (as 8- to 10-year-olds
492 was the youngest age group in which we found a significant difference in TOJ performance
493 between the 2-object and 3-object clips, see Table 1), and that susceptibility to this effect
494 increases with age. Somewhat surprisingly, the two youngest groups of children (4- to 6- and
495 6- to 8-year-olds) were equally likely to correctly report the identity of the square that moved
496 first (C) in the 2-object and 3-object clips and were highly accurate in both cases, providing
497 no evidence that the inclusion of object A led them to reorder events in this version of the
498 task. Furthermore, 4- to 6-year-olds were significantly more likely to report the correct order
499 of events in the pseudocollision than adults.

500 The child CJ data, on the other hand, largely mirror what we found in Experiment 1—
501 all age groups were significantly more likely to incorrectly report perceiving a collision in the
502 3-object pseudocollision than the 2-object control clip, and responses did not differ
503 significantly across age groups. Thus, we see an intriguing difference in the pattern of
504 performance across our two measures for the youngest children—their CJs suggest that they
505 viewed B as bumping into C in the 3-object clip, but they do not report reordering in their
506 TOJs. Specifically, while almost all children in the youngest group provided the correct
507 response to the TOJ question for both clips (providing no evidence for reordering), around

508 60% of them incorrectly reported perceiving a collision between B and C in the 3-object clip,
509 which suggests that the inclusion of object A *did* generate an impression of causality for
510 them.

511 The results of Experiment 2 raise two distinct questions: (1) what might explain the
512 difference in children’s TOJ responses between Experiments 1 and 2, and (2) how can we
513 reconcile the difference between young children’s TOJ data and CJ data in Experiment 2? We
514 will start by addressing the first question. One possibility is that young children really do
515 experience the correct order of events in the 3-object clip (i.e., the increasing susceptibility to
516 reordering with age result of Experiment 2 is valid) but something about the procedure in
517 Experiment 1 led them to give answers that misleadingly suggested they reordered the events.
518 Alternatively, perhaps children really do reorder events in line with causality (i.e., the
519 Experiment 1 TOJ result is valid), but something about the procedure in Experiment 2 leads
520 them to give an answer that misleadingly suggests they did not reorder the events. Finally, it
521 seems feasible that the results of both experiments are valid, but the modifications we made
522 to the procedure in Experiment 2 led young children to ignore object A (circle) and focus
523 solely on the two squares; thus they performed comparably in the 2-object and 3-object clips.

524 To elaborate on this potential ‘ignore object A’ explanation for the Experiment 2 TOJ
525 data: in Experiment 1 the practice trials encouraged participants to attend to the entire display
526 because all shapes were squares, and the TOJ question differed between clips—sometimes
527 participants were asked about which square moved first, and sometimes about which moved
528 last. Thus, when they saw the critical clip they were likely attending to the entire display,
529 including object A, which is presumably critical for the reordering effect to occur given that
530 without attending to object A, the 3-object clip is identical to the 2-object control clip. During
531 the practice trials of Experiment 2, on the other hand, participants were primed to attend only
532 to the 2 squares (B and C), as they were only ever asked about these shapes, and furthermore

533 they were only ever asked which one moved first. Thus, when they saw the 3-object
534 pseudocollision they may have completely ignored the circle and focussed their attention only
535 on the two squares (B and C), and specifically on which one moved first (anecdotally, some
536 children reported that they were using this strategy).

537 If this explanation is correct, then why were younger children’s TOJs more affected
538 by the changes to the task (and adults apparently unaffected)? One possibility is that the
539 causal impression generated by the clip is more irresistible to older children and adults
540 because of their more extensive experience of a variety of causal systems and, hence, stronger
541 priors—perhaps we become less able to ‘escape’ the impression of causality as we get older
542 (Bechlivanidis, 2015).

543 Turning to the second question of how to reconcile the difference between young
544 children’s TOJ data and CJ data in Experiment 2, we see two possibilities. First, perhaps
545 young children’s CJ data, which in both experiments suggests they had a causal impression,
546 could be explained by children glossing the test question as a question about whether there
547 was a collision in the clip rather than interpreting it as a question about B and C. Specifically,
548 perhaps these young children incorrectly say “yes” because they do perceive *a* collision
549 (between objects A and B), but they do not actually perceive contact between objects B and
550 C. (We note that one difficulty with this interpretation is that it seems inconsistent with the
551 ‘ignore A’ explanation of the young children’s TOJ data, because it suggests that children
552 paid sufficient attention to A to perceive it making contact with B). The second possibility is
553 that both TOJ and CJ data are valid in Experiment 2, i.e., there is a genuine difference
554 between how collision perception and temporal order perception are affected by the causality
555 manipulation in the youngest group. That is, perhaps in this youngest group, participants have
556 the impression that B collided with C, but their temporal order judgements are not affected by
557 the causality manipulation in the way that older participants’ judgements are.

558 In Experiment 3 we attempted to reduce the likelihood of participants engaging in an
559 ‘ignore A’ strategy by presenting a series of practice clips that encouraged them to attend to
560 all three shapes. If only attending to objects B and C was driving the pattern of TOJ responses
561 in Experiment 2, then young children should revert to reordering (replicating the results of
562 Experiment 1). If on the other hand younger children really are less susceptible to causal
563 reordering then we should replicate the results of Experiment 2.

564 **Experiment 3**

565 The critical clips and questions that followed were the same as in Experiment 2
566 (Figure 2a[ii] and 2b). However, to encourage participants to attend to all of the shapes
567 (which may not have been the case in Experiment 2 and could explain the lack of reordering
568 in young children compared to in Experiment 1) we made some changes to the practice clips.
569 Specifically, we aimed to create a situation in which, by the time the critical clips were
570 viewed, participants did not know which shape they would be asked about. We did this by
571 varying which object we asked about between practice trials: on some trials we asked which
572 *shape* moved first, and in others we asked which *circle* moved first. Then, on the critical
573 trials we asked which *square* moved first (Figure 1c).

574 **Method**

575 **Participants.** Our final sample consisted of 54 adults (40 female, 3-object: N = 28,
576 $M_{\text{age}} = 19$ years; 2-object: N = 26, $M_{\text{age}} = 19$ years) and 197 children (119 female), none of
577 whom had participated in Experiments 1—2. An additional two children were tested but
578 excluded because they were inattentive (N=1), or because they repeatedly responded “don’t
579 know” to the questions (N=1). The child sample was divided into 3 age groups per condition:
580 4- to 6-year-olds (3-object: N = 34, $M_{\text{age}} = 5$ years 1 month; 2-object: N = 32, $M_{\text{age}} = 5$ years
581 5 months), 6- to 8-year-olds (3-object: N = 34, $M_{\text{age}} = 7$ years 1 month; 2-object: N = 31, M_{age}

582 = 7 years 0 months) and 8- to 10-year-olds (3-object: N = 34, M_{age} = 9 years 7 months; 2-
583 object: N = 31, M_{age} = 9 years 1 month).

584 **Materials.** The materials were the same as in Experiments 1 and 2 but we again
585 changed the colours of the shapes to red, blue and yellow (because a few of the youngest
586 children were unsure of the colour grey in Experiment 2).

587 **Procedure.** Participants saw three non-causal practice clips (Figure 1 c): two clips
588 with one square and one circle, and one clip with two circles and a square. After the 2-object
589 practice clips participants were asked “which *shape* moved first?” and the correct answer was
590 the circle for one clip, and the square for the other clip. After the 3-object practice clip
591 participants were asked “which *circle* moved first?” The critical clips (2-object control clip
592 and 3-object pseudocollision) were the same as in Experiment 2 (Figure 2a[ii] and 2b).

593 **Results**

594 **Practice clips.** Performance in the 2-object practice clips ranged from 76% of
595 participants responding correctly (4- to 6-year-olds) to 95% of participants responding
596 correctly (adults). Performance in the 3-object practice clip ranged from 55% of participants
597 responding correctly (4- to 6-year-olds) to 94% of participants responding correctly (adults,
598 see Table S2 for full details).

599 **Pre-registered confirmatory analyses.** Across all age groups, the majority of
600 participants responded correctly to the TOJ question (that C moved first) in the 2-object
601 control clip (Figure 5a). As in Experiment 2, there was a pattern of decreasing response
602 accuracy in the TOJ question for the 3-object pseudocollision (blue bars of Figure 5a):
603 younger children were again more likely to respond correctly than older children and adults
604 when asked “Which square moved first?” Comparisons of TOJ responses between the 2-
605 object and 3-object clips revealed that while 6- to 8-year-olds, 8- to 10-year-olds and adults

606 were significantly more likely to respond correctly in the 2-object clip (Chi square tests, $ps \leq$
607 0.002, Table 1), the 4- to 6-year-olds' performance did not differ significantly between the
608 two critical clips (Fisher's Exact Test, $p = 0.108$, Table 1). As in Experiments 1 and 2,
609 participants in all age groups were significantly more likely to say square B collided with
610 square C in the 3-object pseudocollision than the 2-object control clip (Figure 5b, Chi-square
611 tests: $ps \leq 0.017$ for all, Table 1).

612 *Figure 5 about here*

613 **Exploratory analyses.** Logistic regression revealed that participants' tendency to
614 report the correct order of events (TOJ question) in the pseudocollision was significantly
615 influenced by age group (Wald $\chi^2 = 11.32$, $df = 3$, $p = 0.010$). Posthoc contrasts with Tukey
616 adjusted p-values for multiple comparisons revealed a significant difference between 4- to 6-
617 year-olds and 8- to 10-year-olds (log odds ratio = 1.69, $p = 0.015$), with the youngest children
618 being more likely to respond correctly/less likely to reorder than the oldest children. There
619 were no other significant differences between groups after adjusting for multiple comparisons
620 ($ps \geq 0.124$ for all other pairs of age groups, Table S5). Participants' tendency to report
621 perceiving a collision between objects B and C (CJ question) in the 3-object pseudocollision
622 was not significantly influenced by age group (Wald $\chi^2 = 1.20$, $df = 3$, $p = 0.754$). These
623 patterns of responding with age group as a categorical predictor were in keeping with
624 analyses of child data only when age in years was included as a continuous predictor (see
625 Table S6). TOJs and CJs were significantly associated for the 3-object pseudocollision—
626 participants who reordered events B and C were more likely to report perceiving a collision
627 between those objects ($\Phi = 0.23$, $p = 0.010$, see Table S7 for details per age group).

628 **Discussion**

629 In Experiment 3, we once again replicated our adult results. Thus, while including
630 practice clips (and potentially simplifying the response measures) reduces susceptibility to
631 causal reordering compared with in a ‘one-shot’ experiment where participants only see the
632 critical clip, it seems that the number and nature of the practice clips does not influence
633 adults’ performance. Even using our simplified paradigm, around 40% of adults reorder the
634 events, and 40-60% incorrectly report perceiving contact between objects B and C.

635 The child data from Experiment 3 is largely comparable to that obtained in
636 Experiment 2—TOJ accuracy for the 3-object pseudocollision decreases with age (8- to -10-
637 year-olds were significantly less accurate than 4- to 6-year-olds), and once again there is a
638 discrepancy between the youngest children’s TOJ responses and their CJ responses. Thus, we
639 did not find any evidence that encouraging young children to attend to all of the objects in the
640 display made them more likely to reorder events in line with causality. It is therefore
641 tempting to conclude that young children really are less susceptible to causal reordering than
642 older children and adults. This conclusion, though, still leaves us to explain why the youngest
643 children’s CJ responses resembled those of adults—there was no significant difference
644 between age groups for the pseudocollision CJ responses. As we pointed out above, there are
645 two possible reasons for this: i) either it is the case that these children’s CJ data is explained
646 by a tendency to interpret the test question as being about whether there was a collision (as
647 opposed to where the collision occurred) or, ii) more radically, children’s perception of
648 collision are affected by the causality manipulation but their temporal order judgements are
649 not.

650 However, a further possible explanation for the observed data remains, which was
651 raised by some anecdotal observations while running Experiment 3 with the younger
652 children. First, a handful of children spontaneously gave a response to the TOJ question for
653 the 3-object pseudocollision (responding that square C moved first) before the experimenter

654 had asked the question. This was despite the fact that, based on the practice trials, the
655 experimenter might feasibly have asked “which *shape* moved first?”, or “which *circle* moved
656 first?” to which the correct answer would have been object A/the circle in both cases. This
657 suggests that these participants may have been responding to something other than the
658 question being asked. Second, one 4-year-old correctly gave the response ‘C’, and then
659 spontaneously said “because it’s in the lead!” This raises the possibility that some children,
660 rather than reporting the motion onset, may be reporting the final spatial position of the
661 objects, taking into account the direction of movement, and this misinterpretation may be
662 more common for younger children. That is, when asked “Which square moved first?” they
663 respond to the question “Which *came* first”, or which went furthest to the right (if motion
664 direction is left-to-right), which is object C. In addition, spontaneous verbalizations by some
665 children also suggested that the TOJ question was being misinterpreted—for example, some
666 children responded that C moved first, but then went on to describe events along the lines of
667 “A moved and hit B, and then that moved and hit C”, which was incompatible with the TOJ
668 response they gave. Finally, it seems unlikely that 4- to 6-year-olds would only respond
669 correctly 52% of the time in the 3-object practice trial, but 83% of the time in the 3-object
670 pseudocollision given that the two clips were similar in terms of their complexity (they both
671 involved three objects, and the relative motion onsets of the objects were identical in the two
672 clip types).

673 If some children are inappropriately responding in this way (i.e., giving their answer
674 on the basis of spatial position on the screen rather reporting temporal order), this could also
675 explain the high levels of A-responding in Experiment 1. Recall that around 40% of the
676 youngest age group gave the response “A” when asked “Which square started moving last?”
677 This seemed baffling as square A was quite clearly the first object to move, but makes sense
678 if some children are responding on the basis of the objects’ final positions (considering

679 direction of movement), as outlined above. Under this account, object A “came last”—it
680 finished spatially “behind” squares B and C. If we assume a similar proportion of the
681 youngest children also responded along these lines in Experiments 2 and 3, that would
682 explain a large chunk of the C-responses (because C “won/came first”), which in these two
683 experiments happened to correspond to the correct answer about which object moved first. A
684 reduction in the proportion of children responding on this “winner/loser” basis across age
685 groups could explain the apparent developmental pattern of younger children appearing to
686 give more accurate TOJs in the 3-object pseudocollision than we observed in Experiments 2
687 and 3. This account could also explain the differential way in which the causality
688 manipulation affected TOJs and CJs—if the aforementioned hypothesis is correct (i.e., some
689 proportion of young children are responding on the basis of which object came first/last),
690 then it seems likely that the CJ data are valid, and younger children’s TOJ data are being
691 influenced by the nature of the TOJ question being asked and do not reflect their actual
692 perception of temporal order.

693 **Experiment 4**

694 In Experiment 4 we replicated Experiment 3, but replaced the 2-object control clip
695 with a 3-object canonical collision where A was a circle and B and C were squares (just like
696 the pseudocollisions in Experiments 2 and 3), so the veridical order of motion was ABC. As
697 in Experiments 2 and 3, we asked participants “which square moved first?” If younger
698 children are making a genuine TOJ, and are as accurate as they appear to be in Experiments 2
699 and 3, then in the canonical clip they should respond “B”. If they still respond “C” then this
700 will provide support for the “winner/loser” spatially-based response outlined above.

701 To address whether the CJ results in the previous experiments might be explained by
702 a tendency to respond “yes” when asked about the 3-object pseudocollision because of the

703 presence of a collision between objects A and B, instead of only asking whether square B
704 bumped into square C, for the critical clips we asked about all pairs of squares in a random
705 order (i.e., Did A bump into B? Did B bump into C? Did A bump into C?). If participants are
706 responding to this question in the way it is intended, for both critical clips participants should
707 respond “yes” for A-B and “no” for A-C. They should also respond “yes” when asked about
708 B-C in the canonical collision; if they also respond “yes” in the pseudocollision then this will
709 provide evidence that participants do indeed perceive the movement of C as caused by B.

710 **Method**

711 **Participants.** Our final sample consisted of 127 children (65 female); 65 4- to 6-year-
712 olds, none of whom had participated in Experiments 1—3 (pseudocollision: $N = 35$, $M_{\text{age}} = 5$
713 years 10 months; canonical collision: $N = 30$, $M_{\text{age}} = 6$ years 1 month) and 62 8- to 10-year-
714 olds (pseudocollision: $N = 32$, $M_{\text{age}} = 8$ years 10 months; canonical collision: $N = 30$, $M_{\text{age}} =$
715 8 years 9 months). An additional 4 children were tested but excluded because they were
716 inattentive ($N=2$), because they could not name the shapes ($N=1$), or because of experimenter
717 error ($N=1$).

718 **Procedure.** The practice clips were the same as for Experiment 3 (Figure 1c). The
719 critical clips consisted of the 3-object pseudocollision (ACB, Figure 2a[ii]) from Experiments
720 2 and 3, and a 3-object canonical collision (ABC, Figure 2c). In the canonical collision,
721 object A moved towards object B and stopped adjacent to it, following which B started
722 moving towards object C. B stopped adjacent to C, and C started moving away from B. As
723 for the pseudocollision, all objects moved at a speed of 30 mm/s.

724 **Results.**

725 **Practice clips.** Performance in the 2-object practice clips was 72% correct responses
726 for 4- to 6-year-olds and 92% correct responses for 8- to 10-year-olds. Performance in the 3-

727 object practice clip was 58% correct responses for 4- to 6-year-olds and 84% correct
728 responses for 8- to 10-year-olds (see Table S1 for full details).

729 **Pre-registered confirmatory analyses.** Four- to six-year-olds' TOJs were
730 significantly less accurate for the canonical collision where the correct response was 'B'
731 (23% correct), than for the reordered pseudocollision where the correct response was 'C'
732 (80% correct, $\chi^2 = 20.87$, $p < 0.001$); in fact, they were equally likely to say that C moved
733 first for the pseudocollision and the canonical clip (Figure 6). The 8- to 10-year-olds on the
734 other hand mostly gave the (correct) response that B moved first in the canonical clip, though
735 30% of participants in this age group still erroneously claimed that C moved first in the
736 canonical clip (Figure 6). The older children were more likely to respond correctly in the
737 canonical clip than in the pseudocollision, but not significantly so (canonical collision: 70%
738 correct, pseudocollision: 59% correct, $\chi^2 = 0.76$, $p = 0.382$).

739 *Figure 6 about here*

740 Participants in both age groups were significantly more likely so respond 'yes' when asked
741 whether A bumped into B (which it did) compared with when asked whether A bumped into
742 C (which it did not), and this was true for both clip types (canonical and reordered, $ps <$
743 0.001 for all, Figure 7).

744 *Figure 7 about here*

745 In both age groups and for both types of clip the majority of participants (>80%) responded
746 'yes' when asked whether B bumped into C (Figure 7). There was no significant difference
747 between the responses children in either age group gave for the canonical collision and the
748 reordered collision when asked whether square B bumped into square C (4- to 6-year-olds: χ^2
749 $= 0.03$, $p = 0.959$; 8- to 10-year-olds: $\chi^2 = 0.336$, $p = 0.562$).

750 **Exploratory analyses.** TOJs and CJs were significantly associated for the 3-object
751 pseudocollision—participants who reordered events B and C were more likely to report
752 perceiving a collision between those objects ($\Phi = 0.31, p = 0.013$, see Table S2 for details
753 per age group).

754 **Discussion**

755 Experiment 4 again replicated the developmental pattern of TOJ responses from
756 Experiments 2 and 3, with younger children appearing to give more accurate TOJs (saying C
757 moved first) than older children for the reordered pseudocollision clip. However, the results
758 for the canonical collision strongly suggest that this does not reflect a better ability to
759 perceive the veridical order of events in early childhood. When shown a canonical collision,
760 older children gave more accurate TOJs than younger children. Specifically, the majority of
761 children in the younger age group responded incorrectly to the TOJ question when presented
762 with a canonical collision where the correct answer was ‘B’, which strongly suggests that
763 they tend to give the response ‘C’ regardless of clip type. Eight- to 10-year-olds on the other
764 hand mostly gave the correct response ‘B’ for the canonical collision, though almost 1/3 still
765 responded ‘C’, suggesting that the TOJ question may also cause problems for some older
766 children. Thus it appears that the majority of young children and some older children may not
767 be interpreting the TOJ question (“which square moved first?”) as it was intended; instead
768 they appear to respond on the basis of which square ‘came first’, choosing a square on the
769 basis of spatial position. Furthermore, as in the previous experiments we did not find the
770 expected association between TOJs and CJs for the youngest group of children.

771 In addition to asking whether square B bumped into square C as in Experiments 1–3,
772 in Experiment 4 we also asked participants for their collision judgements about the other
773 pairs of shapes. This enabled us to establish that children of all of the ages tested do indeed

774 understand the collision question and interpret it correctly (i.e., they are able to correctly
775 identify the presence/absence of a ‘bump’ between object pairs) – they typically say ‘yes’
776 when asked whether A bumped into B, and ‘no’ when asked whether A bumped into C.
777 Interestingly, > 80 % of participants in both age groups reported (incorrectly) that B did
778 bump into C in the pseudocollision. Given that a comparable percentage of participants gave
779 this response for the canonical collision, this provides strong evidence that the causal
780 impression generated by the pseudocollision is similar to that generated by the canonical
781 collision.

782 **General Discussion**

783 Across four experiments we investigated whether children, like adults, reorder events
784 in line with causality. We modified an existing adult paradigm (Bechlivanidis & Lagnado,
785 2016) for this purpose: in each experiment participants watched a 3-object pseudocollision in
786 which the order of events was manipulated so that, unlike in a canonical collision, the third
787 object in line (C) moved *before* the middle object (B) (i.e., the order of motion onset was
788 ACB, and object B never collided with object C). They were then asked (a) a temporal order
789 judgement (TOJ) question and (b) a collision judgement (CJ) question (three in Experiment
790 4). If participants reorder events in line with causality, then they should incorrectly report that
791 B moved before C. If the introduction of A affects whether they perceive a collision between
792 B and C, they should also incorrectly report that B bumped into C.

793 Overall, we found evidence that the causality manipulation affected children’s
794 perception of the order of events in the sequence. Across all four experiments participants in
795 all age groups (including adults) were significantly more likely to report perceiving a
796 collision between objects B and C in the 3-object pseudocollision than in the 2-object control
797 clip, despite the spatiotemporal relations between B and C being identical in the two clips.

798 Furthermore, CJs did not differ significantly between age groups (apart from in Experiment
799 1, where 9- to 10-year-olds were more likely to report a collision than 7- to 9-year-olds). We
800 also found evidence for reordering according to our TOJ measure in the majority of age
801 groups: from 4 years in Experiment 1, from 8 years in Experiment 2, and from 6 years in
802 Experiment 3. However, our two measures were not consistently associated with one another
803 (see supplementary Table S7) and the TOJ data from the younger children showed an
804 interesting pattern of results that warrants further discussion.

805 Although TOJ responses in Experiment 1 provided evidence for reordering in all age
806 groups, taken at face value the subsequent TOJ results from Experiments 2 and 3 suggested
807 that younger children did not reorder events, and may in fact have been more accurate than
808 older children and adults in their perception of the order of events. However, Experiment 4
809 demonstrated that some children—particularly in the younger age range—had a systematic
810 tendency to respond based on spatial rather than temporal information when asked “Which
811 square moved first?” Specifically, when shown a canonical collision where the order of
812 motion onset was ABC, the majority of young children still reported that C moved first (i.e.,
813 before B). Thus, it appears that some children respond on the basis of which square ‘came
814 first’, rather than which started to move first. This basis for responding can also explain the
815 large proportion of young children saying that object A started moving last in Experiment
816 1—in this case, A ‘came last’.

817 Despite deliberately avoiding use of the terms ‘before’ or ‘after’ in our TOJ questions,
818 our results demonstrate that, at least under these circumstances, asking which object moved
819 first/last is also not an appropriate measure of very young children’s temporal order
820 perception in this context (i.e., when there is a possible spatial interpretation of the question).
821 The general idea that young children are likely to (erroneously) focus on spatial rather than
822 temporal cues has a long history within developmental psychology (Piaget, 1969; see

823 McCormack, 2015, for historical review). The current findings add to the body of evidence
824 that suggests that young children may privilege spatial information, perhaps because of the
825 more concrete nature of spatial cues (Casasanto & Boroditsky, 2007; Casasanto,
826 Fotakopoulou, & Boroditsky, 2010).

827 However, Experiment 4 also confirmed that young children’s collision judgements
828 were valid: following the canonical clip, they were able to accurately identify the presence
829 (between A and B) and absence (between A and C) of a ‘bump’ between objects. Taken
830 together with the CJ results for Experiments 1-3, this suggests that the inclusion of object A
831 generates a causal impression that modulates children’s experience of the subsequent motion
832 of B and C. In Experiment 4, children in both age groups were equally likely to report
833 perceiving a collision between B and C in the pseudocollision (where there was no collision
834 between these objects) and in a 3-object canonical collision (where there actually was a
835 collision between B and C). This suggests that for 4- to 10-year-olds, as for adults, the
836 pseudocollision generates the same impression of causality as a genuine collision.

837 What then should we conclude about the developmental profile of the reordering
838 effect? Setting aside the data from the youngest age group (4- to 6-year-olds), there was no
839 evidence across Experiments 1—3 that susceptibility to the causal reordering effect increases
840 with age. This suggests that causal reordering is present in children, as it is in adults, and that
841 it remains stable over development. The key issue is whether we should conclude that this
842 effect is also present in early childhood, in 4- to 6-year-olds. As we have pointed out, across
843 four experiments the CJ data from this age group consistently suggested that they are as
844 likely as older children and adults to mistakenly report that B collided with C in the 3-object
845 clip. The data from Experiment 4 indicate that there is no reason to assume that the causality
846 manipulation genuinely had a differential effect on young children’s collision perception and
847 their temporal order perception; rather, their temporal order judgements were unreliable. The

848 4- to 6-year-olds' performance in the 3-object practice clips—where it was not possible to
849 respond on the basis of a spatial strategy—were poor compared with other age groups,
850 suggesting that children in this age group may have difficulties tracking and remembering the
851 order of motion onset of three objects. Thus, the most conservative conclusion is that we do
852 not yet know whether 4- to 6-year-olds show the causal reordering effect. However, taken
853 alongside children's CJ data, we believe that the findings of Experiment 1 provide a good
854 reason for believing that causal reordering is indeed evident in this age group. Unlike in
855 Experiments 2—4, we can exclude children in Experiment 1 who responded to the TOJ
856 question on the basis of spatial position: these are the children who reported that A started
857 moving last. Indeed, our existing analysis excluded these children (based on our pre-
858 registered confirmatory analysis plan), and a substantial majority of the remaining children in
859 this group (76%) reported that C was the last object to move in the 3-object pseudocollision
860 clip (but not in the 2-object clip). Thus, the findings of Experiment 1 suggest that causal
861 reordering is present even in 4- to 6-year-olds.

862 In sum, we believe that our findings provide evidence for an early-developing role of
863 causality in interpreting the environment. While infants' causal perception has previously
864 been shown to be influenced by bottom-up visual factors in a comparable way to adults' (e.g.,
865 the grouping effect, Choi & Scholl, 2004; Newman et al., 2008), the present study
866 demonstrates that children's causal perception can also exert top-down effects on their
867 temporal perception, as is the case for adults (Bechlivanidis & Lagnado, 2016). This evidence
868 that causality can influence children's experience of time is in keeping with recent research
869 showing that children as young as four years are susceptible to temporal binding—with
870 children predicting that events will occur earlier if they are causally connected to a preceding
871 event, compared to when it is preceded by an arbitrary predictive signal (Blakey et al., 2018).
872 Thus, it appears that not only do children use temporal cues to make causal judgements (e.g.,

873 Bullock & Gelman, 1979; McCormack et al., 2015; Mendelson & Shultz, 1976; Rankin &
874 McCormack, 2013; Schlottmann et al., 1999); they also use causal cues to make temporal
875 judgements—about the duration between events, and about the order in which events
876 occurred.

877 Although the results presented in the current study are illuminating with respect to the
878 developmental trajectory of causal reordering, important questions remain regarding the
879 mechanism underpinning the effect. Properly answering these questions is beyond the scope
880 of the present study, and will require developing new paradigms to distinguish between
881 possible explanations of the reordering effect. Nevertheless, in what follows we outline these
882 different potential explanations, discuss what has been established to date, and describe our
883 ongoing work with adults that aims to generate new evidence to definitively distinguish
884 between these alternative explanations.

885 There are three distinct types of explanation that might account for the reordering
886 effect, which are set out by Bechlivanidis and Lagnado (2016). First, it is possible that when
887 viewing the 3-object pseudocollision participants fail to see all of the events and so they do
888 not actually perceive their order (inattention). Specifically, it is plausible that the motion of
889 object B could be missed, as attention is diverted by the motion onset of object C. On such an
890 explanation, reordering occurs because participants ‘fill in’ the missing information by
891 making a *post hoc* inference on the basis of the most likely order of events, given their causal
892 impression. Arguably this is the least interesting explanation of the effect, because it suggests
893 that participants simply speculate about what might have happened, rather than their
894 judgments being based on processing the events that they were presented with. Second, the
895 reordering effect could occur if participants do attend to and accurately perceive the order of
896 all events, but because of the causal impression generated by the clip, the memory of events
897 they ultimately retrieve is of the more plausible causal order (misremembering). Finally, it

898 may be the case that participants' original representation of the temporal order of events
899 matches the causal order rather than the objective order—i.e., they actually perceive events
900 happening in an order that does not reflect reality (misperceiving). This last possibility is
901 particularly interesting, because it challenges what might be seen as the intuitive view of
902 perception, namely that events are perceived in the order in which they occur, so that the
903 temporal structure of experience simply mirrors the temporal structure of events in the world
904 (Hoerl, 2013; Phillips, 2014).

905 Previous findings with adults speak against the inattention account of reordering (that
906 participants do not attend to all of the objects in the pseudocollision). When participants first
907 watch a pseudocollision, and are subsequently presented with a pseudocollision and a
908 canonical collision side by side, they tend to mistake the pseudocollision they initially saw
909 for the canonical collision. In contrast, when they are first presented with a slightly modified
910 pseudocollision clip in which B does not move at all, this is detected by most people and they
911 are able to identify it as the clip they saw, rather than mistaking it for a canonical collision
912 (Experiment 2, Bechlivanidis & Lagnado, 2016). This suggests that participants apparently
913 do attend to the behaviour of object B—they are not simply filling in missing information
914 *post hoc* because they did not see what happened. However, this study could not distinguish
915 between 'misremembering' and 'misperceiving' accounts of the reordering effect.

916 Distinguishing between these two accounts is difficult because in the studies to date
917 participants have made their judgments after the events have happened. Ideally, in order to
918 examine what participants perceive (rather than what they construct in memory), a paradigm
919 would be used that taps into the processes that occur while the events themselves unfold.
920 However, given the very short time scales over which the events happen, such a paradigm
921 could not involve participants making explicit verbal judgments, as such judgments are by
922 necessity *post-hoc*. We are currently testing a paradigm with adults that we believe taps into

923 the processes that occur as the events unfold, in which participants have to synchronize the
924 occurrence of another unrelated event with the onset of movement of B or C. In this task,
925 participants are given multiple opportunities to view the pseudocollision and adjust the timing
926 of the unrelated event so that they perceive it as occurring simultaneously either with the
927 movement of B or the movement of C. If causal reordering stems from a genuine perceptual
928 effect (participants perceive B moving before C), then the temporal location of events should
929 be shifted to match causal assumptions—when synching with B, participants should place the
930 unrelated event earlier than the actual onset of B’s motion, and when synching with C they
931 should place the unrelated event later than the actual onset of motion. If instead participants
932 accurately perceive the order of events (they perceive C moving before B) and it is only later
933 that their causal impression interferes with their temporal order judgement, then their
934 placements of the unrelated event should reflect the veridical timing of B’s and C’s motion
935 onset.

936 Depending on our adult findings, we hope to subsequently explore whether this task
937 can also be adapted for use with children, although the task is likely to be more challenging
938 than the one used in the current study because of the need for multiple trials in which
939 millisecond timing adjustments are made (though see Blakey et al., 2018). We should
940 emphasize, though, that in our view the developmental profile of the reordering effect is
941 interesting regardless of whether a misremembering or misperceiving explanation of it is
942 correct. This is because, regardless of which of these explanations is correct, reordering
943 serves as a novel demonstration of how causal assumptions have top-down effects on basic
944 processes. Establishing whether such assumptions play a similar role in children sheds light
945 on the extent to which causal cognition plays a similar fundamental role from early in
946 development.

947 Thus, the current findings are informative with regards to children’s causal reasoning
948 abilities more broadly. First, our results add to the small body of work suggesting that
949 children’s perception of physical causation is largely similar to that of adults (Schlottmann,
950 Allan, et al., 2002; Schlottmann, Cole, et al., 2013). Previous research has used simple two-
951 object displays and indicated that the introduction of delays or spatial gaps reduces the
952 likelihood that children perceive physical causation (Schlottmann et al., 2013); in this respect
953 children largely resemble adults. However, the pseudocollision presented to children in the
954 present study apparently generated a causal impression (as participants reported that B
955 bumped into C), even though no contact was made and C moved before B. As with adult
956 findings (Bechlivanidis & Lagnado, 2016), these results suggest that, rather than causal
957 impressions being determined only by the basic spatial-temporal properties of object
958 movement, schemata—in this case, a series of collisions—are used in a top-down manner in
959 the interpretation of perceptual displays. Such schemata appear to be used in the same way in
960 young children as in adults. Second, a large body of previous work has demonstrated that
961 young children are able to use the causal structure of events in the world to make inferences
962 and guide their behaviour (e.g., Muentener & Schulz, 2016; Sobel & Legare, 2014). Causal
963 reasoning has been proposed to play an important role in diverse domains, including
964 children’s understanding of the physical world (e.g., Baillargeon, 2004), the development of
965 morality (e.g., Hamlin, 2013), and the generation of explanations (e.g., Legare, 2012). The
966 present study extends the evidence on the influence of causality on children’s experience of
967 the world to another domain: their experience of time. Thus, the current results add to a
968 growing body of evidence that causality plays a fundamental role in our experience of the
969 world from early in development.

970 On the assumption that the present study has demonstrated that children as young as
971 four years reorder events to match a causal interpretation, further work is needed to establish

972 the developmental origins of this temporal illusion. For example, a habituation paradigm
973 could be used to test whether or not infants discriminate between a canonical 3-object
974 collision and the reordered pseudocollision. There would also be value in developing a
975 paradigm appropriate for comparative studies to enable investigation of the evolutionary
976 origins of causal reordering. While ‘higher’ causal knowledge and inference has been
977 reasonably widely explored in non-human animals (e.g., Seed & Call, 2009), there have been
978 relatively few studies of causal perception. Recent research has demonstrated that
979 chimpanzees are susceptible to causal capture, in which a causal impression can induce
980 perceptual alteration of the spatiotemporal properties of co-occurring events (Matsuno &
981 Tomonaga, 2017; Scholl & Nakamaya, 2002). This provides initial evidence that causality
982 also influences the visual perception of our closest ape relatives, but just how
983 phylogenetically widespread susceptibility to causality-based temporal illusions might be
984 remains an open question.

985 To conclude, the findings reported in the present study add to a small but growing
986 body of evidence demonstrating an early-developing bidirectional relation between time and
987 causality (Blakey et al., 2018; Lorimer et al., 2017). The current study extends this research
988 by showing that children’s causal impressions can qualitatively alter their temporal
989 experience—through the reordering of events to match a causal interpretation.

990 **References**

- 991 Baillargeon, R. (2004). Infants’ Physical World. *Current Directions in Psychological*
992 *Science*, 13(3), 89–94. <https://doi.org/10.1111/j.0963-7214.2004.00281.x>
- 993 Bechlivanidis, C. (2015). *The arrow of time through the causal lens: When causal beliefs*
994 *determine temporal order*. Doctoral dissertation, UCL (University College London).

- 995 Bechlivanidis, C. & Lagnado, D. A. (2016). Time reordered: Causal perception guides the
996 interpretation of temporal order, *Cognition*, 146, 58-66.
997 <https://doi.org/10.1016/j.cognition.2015.09.001>
- 998 Bechlivanidis, C., & Lagnado, D. A. (2013). Does the “why” tell us the “when”?
999 *Psychological Science*, 24(8), 1563-1572. <https://doi.org/10.1177/0956797613476046>
- 1000 Bechlivanidis, C., Schlottmann, A., Lagnado, D.A. (2019) Causation Without Realism
1001 *Journal Of Experimental Psychology: General*, 148(5), 785-804. doi:
1002 10.1037/xge0000602
- 1003 Blakey, E., Tecwyn, E. C., McCormack, T., Lagnado, D. A., Hoerl, C., Lorimer, S. &
1004 Buehner, M. J. (2018) When Causality Shapes the Experience of Time: Evidence for
1005 Temporal Binding in Young Children. *Developmental Science*, e12769.
1006 <https://doi.org/10.1111/desc.12769>
- 1007 Blything, L. P., & Cain, K. (2016). Children’s processing and comprehension of complex
1008 sentences containing temporal connectives: The influence of memory on the time
1009 course of accurate responses. *Developmental Psychology*, 52(10), 1517.
1010 <http://dx.doi.org/10.1037/dev0000201>
- 1011 Blything, L. P., Davies, R., & Cain, K. (2015). Young children's comprehension of temporal
1012 relations in complex sentences: The influence of memory on performance. *Child*
1013 *Development*, 86(6), 1922-1934. DOI: 10.1111/cdev.12412
- 1014 Borhani, K., Beck, B., & Haggard, P. (2017). Choosing, doing, and controlling: implicit sense
1015 of agency over somatosensory events. *Psychological Science*, 28(7), 882-893.
1016 10.1177/0956797617697693

1017 Buehner, M. J., (2012). Understanding the past, predicting the future: Causation, not
1018 intentional action, is the root of temporal binding. *Psychological Science*, 23, 1490-
1019 1497. <https://doi.org/10.1177/0956797612444612>

1020 Buehner, M. J. (2015). Awareness of voluntary and involuntary causal actions and their
1021 outcomes. *Psychology of Consciousness: Theory, Research, and Practice*, 2(3), 237-
1022 252. DOI:10.1037/cns0000068

1023 Buehner, M. J., & Humphreys, G. R. (2009). Causal binding of actions to their effects.
1024 *Psychological Science*, 20, 1221-1228. [https://doi.org/10.1111/j.1467-](https://doi.org/10.1111/j.1467-9280.2009.02435.x)
1025 [9280.2009.02435.x](https://doi.org/10.1111/j.1467-9280.2009.02435.x)

1026 Buehner, M. J., & May, J. (2003). Rethinking temporal contiguity and the judgement of
1027 causality: Effects of prior knowledge, experience, and reinforcement procedure. *The*
1028 *Quarterly Journal of Experimental Psychology Section A*, 56(5), 865-890.
1029 DOI:10.1080/02724980244000675

1030 Bullock, M., & Gelman, R. (1979). Preschool children's assumptions about cause and effect:
1031 temporal ordering. *Child Development*, 50, 89–96. DOI: 10.2307/1129045.

1032 Casasanto, D., & Boroditsky, L. (2007). Time in the mind: Using space to think about time.
1033 *Cognition*, 106, 579-593. <https://doi.org/10.1016/j.cognition.2007.03.004>

1034 Casansanto, D., Fotakopoulou, O., & Boroditsky, L. (2010). Space and time in the child's
1035 mind: Evidence for a cross-dimensional asymmetry. *Cognitive Science*, 34, 387-405.
1036 <https://doi.org/10.1111/j.1551-6709.2010.01094.x>

1037 Cavazzana, A., Begliomini, C., & Bisiacchi, P. S. (2014). Intentional binding effect in
1038 children: insights from a new paradigm. *Frontiers in Human Neuroscience*, 8, 651.
1039 <https://doi.org/10.3389/fnhum.2014.00651>

1040 Cavazzana, A., Begliomini, C., & Bisiacchi, P. S. (2017). Intentional binding as a marker of
1041 agency across the lifespan. *Consciousness and Cognition*, 52, 104-114.
1042 <https://doi.org/10.1016/j.concog.2017.04.016>

1043 Choi, H., & Scholl, B. J. (2004). Effects of grouping and attention on the perception of
1044 causality. *Perception & Psychophysics*, 66(6), 926-942. DOI: 10.3758/BF03194985

1045 Cohen, L. B., & Amsel, G. (1998). Precursors to infants' perception of the causality of a
1046 simple event. *Infant Behavior and Development*, 21(4), 713-731. DOI:
1047 10.1016/S0163-6383(98)90040-6

1048 Desantis, A., Waszak, F., Moutsopoulou, K., & Haggard, P. (2016). How action structures
1049 time: about the perceived temporal order of action and predicted
1050 outcomes. *Cognition*, 146, 100-109. DOI: 10.1016/j.cognition.2015.08.011

1051 Faro, D., McGill, A. L., & Hastie, R. (2013). The influence of perceived causation on
1052 judgements of time: an integrative review and implications for decision-
1053 making. *Frontiers in Psychology*, 4, 217. DOI: 10.3389/fpsyg.2013.00217

1054 Hamlin, J. K. (2013). Moral Judgment and Action in Preverbal Infants and Toddlers:
1055 Evidence for an Innate Moral Core. *Current Directions in Psychological Science*,
1056 22(3), 186–193. <https://doi.org/10.1177/0963721412470687>

1057 Hoerl, C. (2013). A succession of feelings, in and of itself, is not a feeling of succession.
1058 *Mind*, 122 (486) (2013), pp. 373-417, 10.1093/mind/fzt070

1059 Lagnado, D. A., & Sloman, S. A. (2006). Time as a guide to cause. *Journal of Experimental*
1060 *Psychology: Learning, Memory, and Cognition*, 32(3), 451. DOI: 10.1037/0278-
1061 7393.32.3.451

1062 Legare, C.H. (2012). Exploring explanation: explaining inconsistent evidence informs
1063 exploratory, hypothesis-testing behavior in young children. *Child Development*, 83 1,
1064 173-85. DOI:10.1111/j.1467-8624.2011.01691.x

1065 Leslie, A. M., & Keeble, S. (1987). Do six-month-old infants perceive
1066 causality? *Cognition*, 25(3), 265-288. DOI: 10.1016/S0010-0277(87)80006-9

1067 Lorimer, S., McCormack, T., Blakey, E., Lagnado, D. A., Hoerl, C., Tecwyn, E.C., &
1068 Buehner, M. J. (under review). The Developmental Profile of Temporal Binding:
1069 From Childhood to Adulthood.

1070 Mascialoni, E., Regolin, L., Vallortigara, G., & Simion, F. (2013). The cradle of causal
1071 reasoning: newborns' preference for physical causality. *Developmental Science*, 16(3),
1072 327-335. <https://doi.org/10.1111/desc.12018>

1073 Matsuno, T., & Tomonaga, M. (2017). Causal capture effects in chimpanzees (*Pan*
1074 *troglydites*). *Cognition*, 158, 153-164. DOI: 10.1016/j.cognition.2016.10.023

1075 McCormack, T. (2015). The development of temporal cognition. *Handbook of Child*
1076 *Psychology and Developmental Science*, 2, 624-670.

1077 Mendelson, R., & Shultz, T. R. (1976). Covariation and temporal contiguity as principles of
1078 causal inference in young children. *Journal of Experimental Child Psychology*, 22(3),
1079 408-412. [https://doi.org/10.1016/0022-0965\(76\)90104-1](https://doi.org/10.1016/0022-0965(76)90104-1)

1080 Merchant, H., & Yarrow, K. (2016). How the motor system both encodes and influences our
1081 sense of time. *Current Opinion in Behavioral Sciences*, 8, 22-27. DOI:
1082 10.1016/j.cobeha.2016.01.006

1083 Muentener, P., & Bonawitz, E. (2017). The Development of Causal Reasoning. In Waldman,
1084 M. R.. (Ed.) *The Oxford Handbook of Causal Reasoning*. Oxford University Press.
1085 DOI: 10.1093/oxfordhb/9780199399550.013.40

1086 Newman, G. E., Choi, H., Wynn, K., & Scholl, B. J. (2008). The origins of causal perception:
1087 Evidence from postdictive processing in infancy. *Cognitive Psychology*, *57*(3), 262-
1088 291. DOI: 10.1016/j.cogpsych.2008.02.003

1089 Oakes, L. M. (1994). Development of infants' use of continuity cues in their perception of
1090 causality. *Developmental Psychology*, *30*(6), 869. DOI: 10.1037/0012-1649.30.6.869

1091 Phillips, I. (2014). Experience of and in Time. *Philosophy Compass*, *9*(2), 131–144.

1092 Piaget, J. (1969). *The child's conception of time*. London: Routledge and Keegan Paul.

1093 R Core Team (2017). R: A language and environment for statistical computing. R Foundation
1094 for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.

1095 Rankin, M. L., & McCormack, T. (2013). The temporal priority principle: at what age does
1096 this develop? *Frontiers in Psychology*, *4*. <https://doi.org/10.3389/fpsyg.2013.00178>.

1097 Saxe, R., & Carey, S. (2006). The perception of causality in infancy. *Acta*
1098 *Psychologica*, *123*(1-2), 144-165. DOI: 10.1016/j.actpsy.2006.05.005

1099 Schlottmann, A. (1999). Seeing in happen and knowing how it works: how children
1100 understand the relation between perceptual causality and underlying mechanism.
1101 *Developmental Psychology*, *35*, 303-317. DOI: 10.1037/0012-1649.35.1.303

1102 Schlottmann, A., Allen, D., Linderoth, C., & Hesketh, S. (2002). Perceptual causality in
1103 children. *Child Development*, *73*, 1656-1677. [https://doi.org/10.1111/1467-](https://doi.org/10.1111/1467-8624.00497)
1104 [8624.00497](https://doi.org/10.1111/1467-8624.00497)

1105 Schlottmann, A., Cole, K., Watts, R., & White, M. (2013). Domain-specific perceptual
1106 causality in children depends on the spatio-temporal configuration, not motion
1107 onset. *Frontiers in Psychology*, *4*, 365. DOI: 10.3389/fpsyg.2013.00365

1108 Scholl, B. J., & Nakayama, K. (2002). Causal capture: Contextual effects on the perception of
1109 collision events. *Psychological Science*, 13(6), 493-498. DOI: 10.1111/1467-
1110 9280.00487

1111 Seed, A., & Call, J. (2009). Causal knowledge for events and objects in animals. In *Rational*
1112 *Animals, Irrational Humans* (pp. 173-188). Keio University.

1113 Sobel, D. M., & Legare, C. H. (2014). Causal learning in children. *Wiley Interdisciplinary*
1114 *Reviews: Cognitive Science*, 5(4), 413-427.

1115 White, P. A. (2018). Perceptual impressions of causality are affected by common fate.
1116 *Psychological Research*, 82(4), 652-664. DOI: 10.1007/s00426-017-0853-y

1117

1118

1119

1120

1121

1122

1123

1124

1125

1126

1127

1128 **Table 1.** Summary of results comparing performance in the 2-object control clip and the 3-
 1129 object pseudocollision for all age groups in Experiments 1—3 for the temporal order judgement
 1130 (TOJ) and collision judgement (CJ) measures.

		Age Group				
	Measure	4 to 6	6 to 7	7 to 9	9 to 10	Adult
Exp. 1	TOJ	$\chi^2 = 29.89$ $p < 0.001$	$\chi^2 = 32.61$ $p < 0.001$	$\chi^2 = 28.13$ $p < 0.001$	$\chi^2 = 40.24$ $p < 0.001$	$\chi^2 = 15.99$ $p < 0.001$
	CJ	$\chi^2 = 10.56$ $p = 0.001$	$\chi^2 = 15.59$ $p < 0.001$	$\chi^2 = 17.21$ $p < 0.001$	$\chi^2 = 32.94$ $p < 0.001$	$\chi^2 = 18.28$ $p < 0.001$
		Age Group				Adults
	Measure	4 to 6	6 to 8	8 to 10		
Exp. 2	TOJ	$p = 0.238^a$	$p = 0.082^a$	$\chi^2 = 8.72$ $p = 0.003$	$\chi^2 = 16.31$ $p < 0.001$	
	CJ	$\chi^2 = 13.89$ $p < 0.001$	$\chi^2 = 9.67$ $p = 0.002$	$\chi^2 = 7.33$ $p = 0.007$	$\chi^2 = 13.12$ $p < 0.001$	
Exp. 3	TOJ	$p = 0.108^a$	$p = 0.002^a$	$\chi^2 = 22.70$ $p < 0.001$	$\chi^2 = 12.83$ $p < 0.001$	
	CJ	$\chi^2 = 5.73$ $p = 0.017$	$\chi^2 = 22.71$ $p < 0.001$	$\chi^2 = 20.75$ $p < 0.001$	$\chi^2 = 14.84$ $p < 0.001$	

1131 ^a Fisher's Exact Test

1132

1133

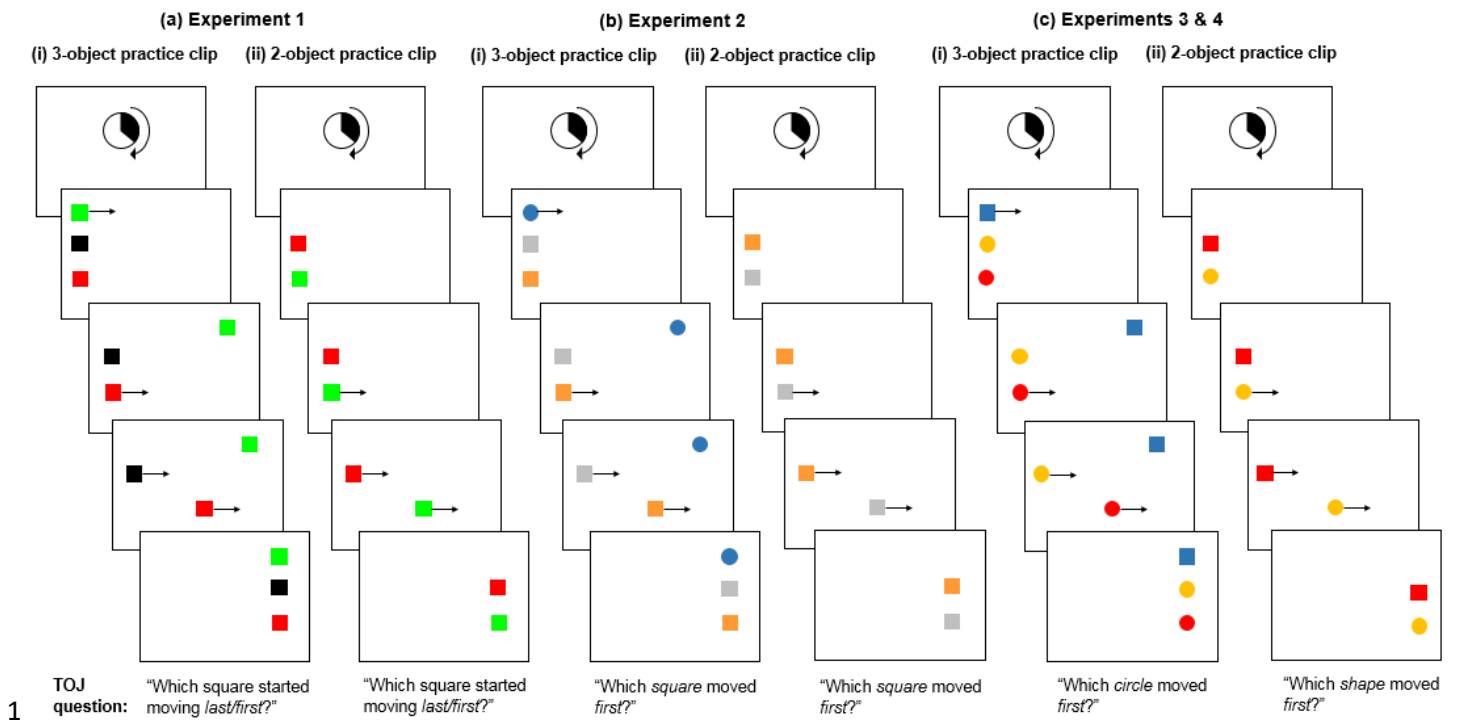
1134

1135

1136

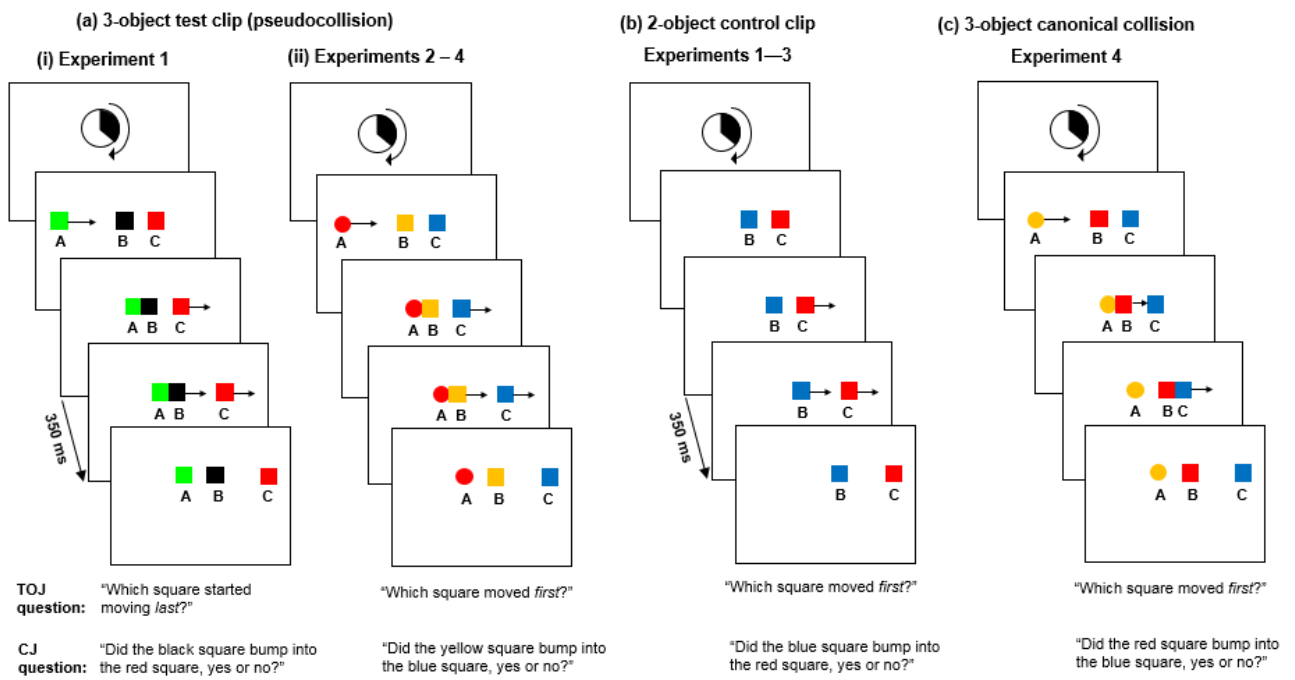
1137

1138



1140 **Figure 1.** Schematic representations of example practice clips seen by participants in (a)
 1141 Experiment 1, (b) Experiment 2 and (c) Experiments 3 and 4, and the TOJ question they were
 1142 asked after each clip. Direction of motion shown is left-to-right, but could also be right-to-left.
 1143 The colours of the objects were randomized between participants. Clips were presented in a
 1144 random order. In Experiment 1 participants saw two clips of each type (3-object and 2-object;
 1145 4 in total) and motion onset order of the shapes was random. They were either asked about
 1146 which square started moving last or first, with the order alternating between clips. In
 1147 Experiment 2 participants saw one clip of each type and the circle always moved first in the 3-
 1148 object clip. In Experiments 3 and 4 participants saw one 3-object clip where the square always
 1149 moved first, and two 2-object clips: one where the circle moved first and one where the square
 1150 moved first (not shown).

1151
 1152
 1153
 1154
 1155
 1156
 1157



1158

1159 **Figure 2.** Schematic representations of (a) the 3-object pseudocollision clip used in [i]
 1160 Experiment 1 and [ii] Experiments 2–4; (b) the 2-object control clip used in Experiments 1—
 1161 3; and (c) the 3-object canonical collision used in Experiment 4, and the TOJ and CJ questions
 1162 participants were asked after each clip. Direction of motion shown is left-to-right, but could
 1163 also be right-to-left. The colours of the objects were randomised between participants. In
 1164 Experiment 2 the colours used were orange, blue and grey (not shown). In Experiment 4,
 1165 participants were asked a CJ question about each pair of shapes (in a random order) for the
 1166 pseudocollision and the canonical collision, so for the example shown for the latter they would
 1167 also have been asked whether the yellow circle bumped into the red square, and whether the
 1168 yellow circle bumped into the blue square.

1169

1170

1171

1172

1173

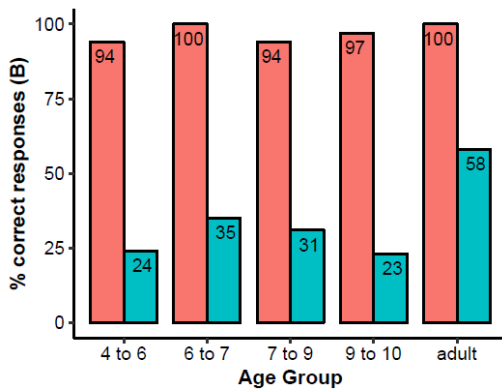
1174

1175

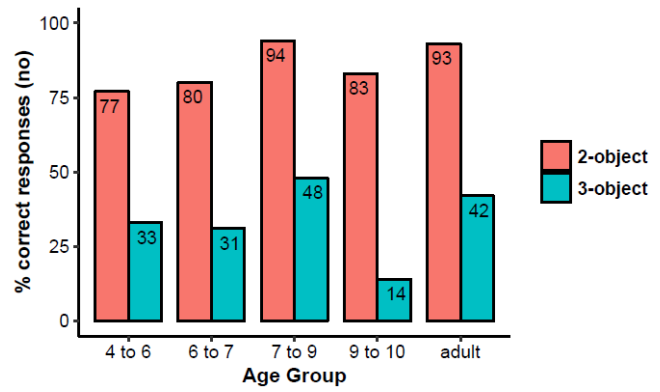
1176

1177
1178

(a) Exp. 1 Temporal order judgements



(b) Exp. 1 Collision judgements

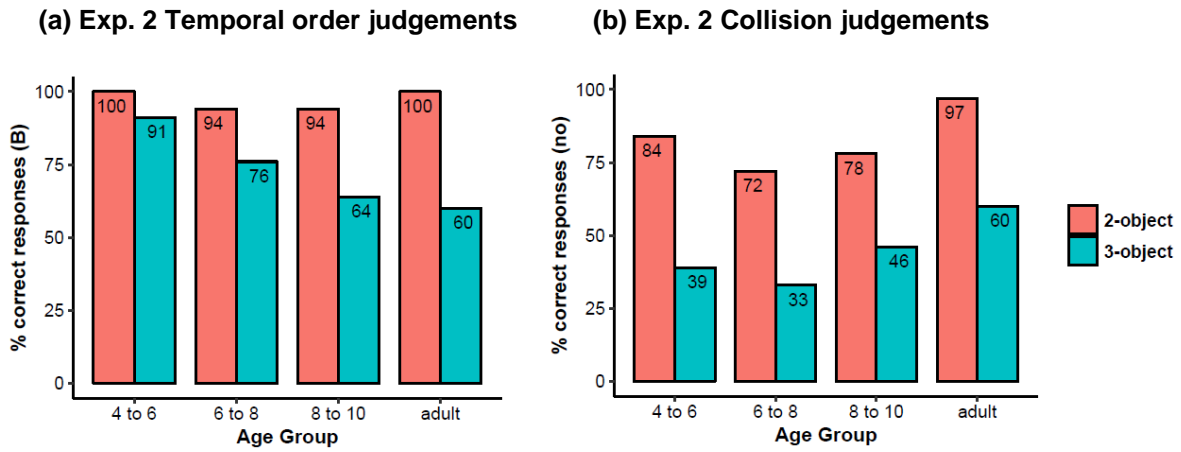


1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189

Figure 3. Percentage of participants in each age group who gave the correct response in (a) the temporal order judgement question (square B); and (b) the collision judgement question (no), in the 2-object control clip (red bars/left-hand bar for each age group) and 3-object pseudocollision (blue bars/right-hand bar for each age group) of Experiment 1.

1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200

1201
1202



1203
1204

1205 **Figure 4.** Percentage of participants in each age group who gave the correct response in (a)
1206 the temporal order judgement question (square C); and (b) the collision judgement question
1207 (no) in the 2-object control clip (red bars/left-hand bar for each age group) and 3-object
1208 pseudocollision (blue bars/right-hand bar per age group) of Experiment 2.
1209

1210

1211

1212

1213

1214

1215

1216

1217

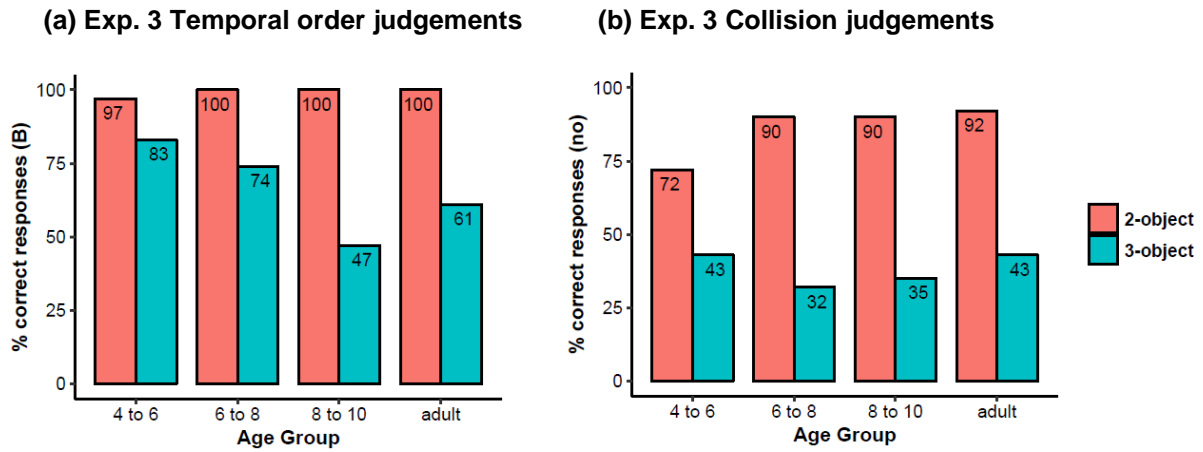
1218

1219

1220

1221

1222
1223



1224
1225

1226 **Figure 5.** Percentage of participants in each age group who gave the correct response in (a) the
1227 temporal order judgement question (square C); and (b) the collision judgement question (no)
1228 in the 2-object control clip (red bars/left-hand bar for each age group) and 3-object
1229 pseudocollision (blue bars/right-hand bar for each age group) of Experiment 3.
1230

1231

1232

1233

1234

1235

1236

1237

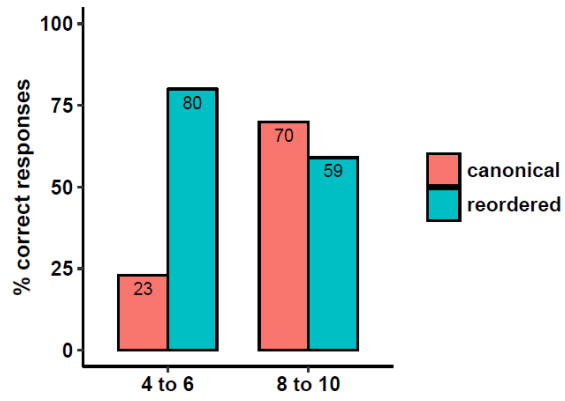
1238

1239

1240

1241

1242



1243

1244 **Figure 6.** Percentage of participants in each age group of Experiment 4 who gave the correct
1245 response for the temporal order judgement question for the canonical collision (red bars/left-
1246 hand bar for each age group, correct answer was B) and the reordered collision (blue bars/right-
1247 hand bar for each age group, correct answer was C).
1248

1249

1250

1251

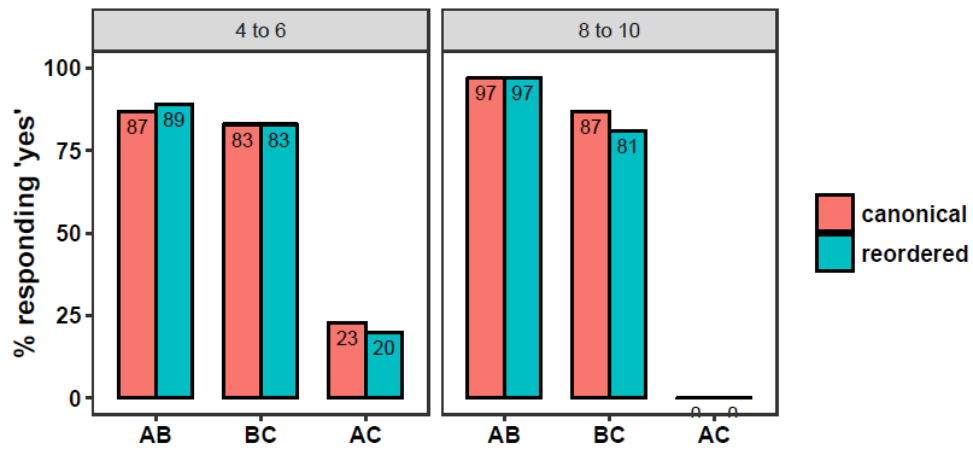
1252

1253

1254

1255

1256



1257

1258 **Figure 7.** Percentage of participants in each age group who responded 'yes' to each of the three
 1259 causal impression questions for the canonical collision (red bars/left-hand bar for each age
 1260 group) and the reordered pseudocollision (blue bars/right-hand bar for each age group).
 1261