

Intersensory binding across space and time: A tutorial review

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Abstract A series of experiments have shown that when a visual and an auditory stimulus are presented simultaneously, they are perceived as a single event. This is known as the *unity assumption* and *modality appropriateness hypothesis*. The present review discusses the evidence for this phenomenon across space and time. The review also discusses the implications of this phenomenon for the understanding of the human auditory system.

Keywords Multisensory integration · Intersensory binding · Unity assumption · Modality appropriateness hypothesis

Introduction

A series of experiments have shown that when a visual and an auditory stimulus are presented simultaneously, they are perceived as a single event. This is known as the *unity assumption* and *modality appropriateness hypothesis*. The present review discusses the evidence for this phenomenon across space and time. The review also discusses the implications of this phenomenon for the understanding of the human auditory system.

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A series of experiments have shown that when a visual and an auditory stimulus are presented simultaneously, they are perceived as a single event. This is known as the *unity assumption* and *modality appropriateness hypothesis*. The present review discusses the evidence for this phenomenon across space and time. The review also discusses the implications of this phenomenon for the understanding of the human auditory system.

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Spatial ventriloquism: Immediate effect

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Temporal ventriloquism: Immediate effect

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Table 1 (continued)

Effect	Task/Paradigm	Main Question	Finding	Sample Study
	AV-TOJ	Change in perception of causality	Counterevidence (not delay) affects dissipation	Machulla, Di Luca, Froehlich and Ernst (2012)
	AV-TOJ	Storage/dissipation of aftereffect	Concurrent estimations and no location constraints	Roseboom and Arnold (2011)
	AV-TOJ	Role of spatial and contextual factors	Spatially specific	Heron et al. (2012)
	Unimodal stimulus detection	Attention modulation of temporal pattern	Recalibration via change in processing speed	Navarra et al. (2009)
	Finger tapping	Generalization of aftereffect	Synchronized finger tapping to flashes/clicks changed	Sugano et al. (2012)
	Magnitude estimation	Population coding in timing	Adaptation not uniform for each SOA	Roach et al. (2011)

(2001). On the other hand, a number of studies have shown that the aftereffect is not only a function of the duration of the stimulus, but also of the frequency of the stimulus (e.g., 2). For example, Roseboom and Arnold (2011) found that the aftereffect is more pronounced for higher frequencies (e.g., 40 Hz) than for lower frequencies (e.g., 5 Hz). This suggests that the aftereffect is not only a function of the duration of the stimulus, but also of the frequency of the stimulus.

In addition, the aftereffect is also influenced by the spatial location of the stimulus. For example, Heron et al. (2012) found that the aftereffect is more pronounced for stimuli presented in the periphery than for stimuli presented in the center. This suggests that the aftereffect is not only a function of the duration of the stimulus, but also of the spatial location of the stimulus.

Finally, the aftereffect is also influenced by the type of stimulus. For example, Navarra et al. (2009) found that the aftereffect is more pronounced for auditory stimuli than for visual stimuli. This suggests that the aftereffect is not only a function of the duration of the stimulus, but also of the type of stimulus.

Table 2 The effects of audiovisual congruency on the aftereffect

	Space	Time
Relative strength	–Vision usually dominates audition, but mutual attraction can be demonstrated	–Audition captures vision
Temporal window	–Audiovisual stimuli need to be presented within ~100 ms (sound-first) to ~300 ms (sound-late)	–Somewhat narrower than for space
Spatial window	~±15° of horizontal separation, but with large variation	–Unconstraint by spatial disparity
Stimulus features	–Greater effect when sounds are difficult to localize	–Sounds with sharp transition
	–Visual stimuli can be presented in focus or periphery	–Visual stimuli preferably in periphery
		–Audiovisual rate <6 Hz
Aftereffect	–Space- and eye-specific (greater at adapted position)	–Modality-specific change in processing speed
	–Greater at adapted frequency, but with mixed evidence about transfer to other frequencies	–Smaller at adapted delay
	–Fast (after single exposure)	–Frequency specific
		–Space specific (simultaneous adaptation to sound-lead and sound-lag possible)
		–Probably fast (possibly after a few exposures)
Role of attention	–Direction of endogenous/exogenous shift of attention and shift in sound location can be dissociated	–Sounds preferably segregated with sharp onsets
	–But arrows and gaze can induce shift sound location as well	–Attention to the audiovisual timing relation increases aftereffect
	–Dual task with focused attention does not decrease the aftereffect	
Audiovisual congruence	–Phonetic congruency in speech: no effect	–Gender-matched speech: more fusion
	–Face orientation: no effect	–Pitch/size congruence: more fusion for congruent pairs
	–Speech/nonspeech mode with sine wave speech: no effect	–Nonspeech like musical instruments: no effect of audiovisual congruency
	–Pitch/size congruence: greater effect for congruent pairs	

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Spatial ventriloquist aftereffects

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Temporal ventriloquist aftereffects

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Spatial and temporal criteria for intersensory pairing

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 g ra f d f n n , n a f
 n f a n b “ nd ” n f a n f a . C n g n ,
 f n a n f a n , ng fa , f f ab fa ,
 b a f a n a f d . n n
 fa a n f a a and fa n f -
 a a a d nd n a a f f f a f
 n f n f b nd g . f f g , f a f ,
 a a f a not a . f a
 - b d nd g a a a f n f -
 n a f f f d fa nd f a nd d
 nd f f nd g an g g f
 n n a “ fa nd ng fa n ” (C n &
 D d f , 2004; D n & , 1980; an a n ,
 Ga n & P , 2007). H a n , n an ad a
 “ a a nd ng fa n ” f n n f

and the fact that the number of trials was 15 (Gdfe, a., 2003; Hf n, a a, Wg an, n, Nff & f, 2003; L ad & G, 2003; f & R an n, 2001; Radg & Bf n, 1977), a g d d a f d a a f ag (a a, Rf n, Hf n, n, Wg an & f, 2004). Ff fa n f q, g, nd f d f n, n fa d a a n f n d n d 200, f a a a d a a a n f. Cn fng fa nd, Mf n-Za f a. (2003) f d a a f d f d f n d f n 200 (Mf n-Za f a., 2003). double-flash n (f a g n f - n b)a n f n d a a n f n d 70 (a a., 2000). and Hff (2007

g f f g n a f f n f -
f g a d g a n f n f n g f a n
and d g f a a n f g f a
a a .

The role of attention for the temporal ventriloquist effect

f b a n a d n a b f a n a “a d - f d”
a n f f a g a a n f a n f a n d
and n b n f a d n f “a d - f d” -
a n f a f a g f d f n n
f a f . f a , g n b f - d a
f a f d a r b f d and f g -
f g , f n a a g n b
n d a n a , n g f a a d a a f a n
d n n a n a a a n . O n b f a n
b f a n a d n f - d a n f n a n
b a a b f n a n f a f a
5 H , f a b f a a d a
a f a d f (B n a n , a n d f g &
f a n , 2008; F a & N d a , 2005, 2007). F a
a . f d a d a a n f n f n
d a d a ‘ d - ” a n a f n d
f a a n d f and a a f b f a g
f a f - f a n a f n f a n n (F a
& N d a , 2005, 2007, 2008, 2010), a d a f f
d n a d f - n f . F f f d n
n f d a a n f n f b n d g n d - b
f a a n n f “ a n d - ” a f a g
(a n d f B g , O f , B n f & f , 2008).
f f f f d a n f a n n f d
f a g g n d) a n a a n f n d
f / r a n a g n a f f f a n
(a n d f B g , G a , O f , f & A a , 2010). f
a d d n , a f g f a n n n d f a
a a n r b f a d f a d f a f a n
d n a n . a a n d
a n n a f f b f a n d a n a f n
(a n d f B g , O f & f , 2012).
I a a a f a d f a f g n d
b g f a d f b a g f n d . K , b g
and f n (2007) a n d n a a O J a n
f a f d g f b d d n a f a n d f
b (f . 7).
a f g n d (f a
a a) a d f a a f a f d f n
a f (, f a n) f a n f
n d . f f n d a f a n f g -
f f d n f n a f g n d d f d f
a n f , a d a n d , d n f a -
g a (n f a d a g f g n d n d f
f a f f f n f n f a f g . A d a

f a n f g f a n d f and
a a a a f f n g . n
f a a n f g f a f “ a f ”
d f and a f a n n b a n d n
a a d a n a , b f n f g , n b n
a n d n a a f a .

The role of attention for the temporal ventriloquist aftereffect

n d g d a f a f a b f a n , a -
f d f d n f a b f f a a a
a a f d a a d a b g g b -
f f n f a a a n a f a a d n
a d a a a a g d n n a n f
(F a a . , 2004; K & f , 2007, 2008 ;
N a f f a a . , 2009; a a a , a & a a n a , 2008;
f n a . , 2004). H f n a . (2012; H f n , R a ,
a f & H a n n , 2010), a g , a d b f f
d f g a d a n n f a f a n
a d a g n b g g d a d a
a d f d n f f a f a n f a d a f .
n b f f a n d d f a f a -
n , a f f a f d f a a -
n n f a n n f a d n a
a f a a . A n d g f a f d f
a d a g f a a f d b a n
n f f a f a b f a n a g f a n
n a d f g a n n a f f a f d f d d
n b b a . a g g a a f -
f a f a b f a n a d n d f n g -
f g a n d a f n a a n f -
g b d a n d f f g .

The role of cognitive factors for intersensory binding

n n f a n f n d n f d a a d n
a b a d (a a n n n) b f f
f n f a n f f n a g b / n f
b / n . a a n f n f b n d g
f n a n a n d f n -
f d a n a n f n f a n a f f
(B f n , 1998; R a d a , 1994 b ; R a d a & B f n ,
1977, 1987). O n d n n a n a f f
n f a n n n d d a n g f a d . A
g g n b b n d g f g f f
g f - f d f g n a f a a f . B f d
a n d a f a d a n f n f b n d g f
a f g f d “ g ” f “ ” n . O n
a f n d f d f a

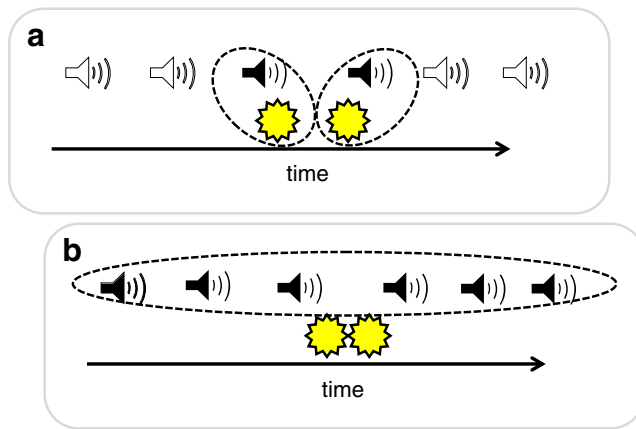


Fig. 7 a and b. n d n a f a n f n d n d d f n
 , f a n a f a . b n n d n d a f
 d n f n d , f n n f b n d g
 a b n d a n g d a n f a . n -
 da g d g f g n a f f f - da d -
 ab nd g (K a ., 2007)

a g f a - a a a g and
 a f n, g a a (g. ., Bf n a ., 1994;
 & M Cf , 1981), f g -
 g (J n, 1953) f b a g d (Rd a &
 Bf n, 1977, E f n l). Rd a and Bf n
 (1977), f a , b nda a f a a
 (g a f) and a d a n g
 a n n f n a d a nd)
 and nd a a n f d d
 a f a a n f gg g a
 f a a an f n a a n f .
 A f n d f d , g , a af -
 n f ad af af af a (g. .,
 a . a). Bf n, n, g faad and d
 G d f (1994) a d d n nd and b and
 f d f d n n n f n n b f f
 ad, n a f a , a nd, f a a / f ara /
 f an af a n dd n d a f . A a
 , b f f a n a n f a a d f n a a ,
 f g f n f d, a af a d a a / f ara / f
 f and (b a n ; g . 8).
 Bf an ad f a : nd f d
 a af n g n nd, and f f d f a ad
 b n ad. f n a n a ada g n
 "f a " f f d (. ., M Gf ; M Gf &
 M D rd a , 1976) n n "f f " nd a
 f b f g and n f d a f f f a
 n a f a g a af n a n
 nd. a a n f f a a f a b g
 f f n nd and a f f g f n (g. .,
 af g a a / and g a a /) f n g f n (af g
 ara / and g a a /). Ff nd , a af d

a a n a and a a - n
b n and n d n a a
a n a b n a d f f n b a
b f n g a b a g d f n a -
f a . On f d n a f f g a f d ,
d g f a f a f d f a
a a a n nd d a n n b a
a d (g. , Ag , Aa & Bf , 2006; K f &
an d Bf , 2005; L n , Mf Lf , Mf , Gf &
Jf n , 2000; Wf a , Gf an a f & n , 2008; Wf a
& n , 2007, 2008). Wf a f f f f a
“n ” n f a d an f d a
f (an and g) a f
g nd f a d (. , and g b g -
g a f n) f a d (. , and
g b g g a d f n f n). Wf n
and a f g nd f g f n , f n -
f b nd g a , ad g a “n ”
f d n f d f n f d f d -
a f a a n f n . b g n d , g ,
f d a n n n d n b b f d n
a f an f f nd f a n n
Wf a a . , 2008). Wf n and b g (2011)
a g d a a f n g f f a
a f a d a d f d n a b f
f a and a a d n n add
n f n , d n - a () f a
d f d and nd g d a a a
a f a d f d . a f a g f a d d
a , d nd g n n , f d a
f n n . g d n a ,
g f nd a n f n and n n

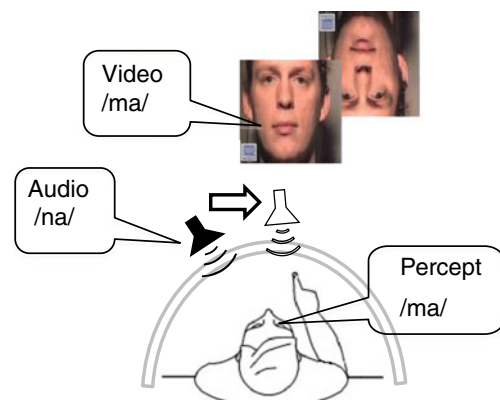


Fig. 8

d equally n a g g d a -
fa f d f. n a , n a d
a f M S f , n d a n
n n n n a n g f a d f a d n
f d a n n . L n f n d b n
n n n d , b n d n d and n b
g g a d a f a f d f a n a d .
d n f f g a n a f g n a f n
n f n f b n d g , a f n , f a f d and
a f f f g .

The role of synesthetic congruency for intersensory binding

An f a f a a n b “ g n ”
a n and, a a n f n f b n d g
synesthetic congruency. n g n , a f -
f d a crossmodal correspondences (n , 2011),
f f n a f a n f f n d n b n -
a f a a d n n a d f d n -
n n b / g n n a d n n (Ean &
f an, 2010; G a a & n , 2006; G an-
M f n , Ó g a , G b n , M b f g & ,
2012; M a a & G b n , 2010; B f & n , 2008,
2009, 2012; n , 2011; n , G an-M f n ,
Ó g a , G b n & , 2012). A an a ,
a a a a g f - d n d n
a f / g b / g f / a f f b and f f - d
n d n a g f / f f d f f n d f b
(H b a d , 1996), a g n a a n n
a f n f (D d , a an, M d & G a an ,
2011). In a f d n a n , B f and
n (2009) f f d a f a f a f d f
and f a a a n n a g n
/ a f (g - a f a g) f f f d -
a g a n n g n a f (g - a g f f
a ; g . 9). n d g a n n b and n
f f n b a f f a g , and f -
d d n f g n a f g n a and
a f a f g b n d g b n n n f
g n a (a B n , n O f , G b & a , 2012;
B f & n , 2008).

I g a b f f g a a n n b
n f a an n g n .
d b B n a . (2012) n g a d - a a -
n n a a n f f f a n f a n a g n
a n (M) and n f a d n a (ERP). A
n B f and n (2009), b f f a d f d
g g a n f f g - d n n
n n f b n d a f a g a f
n a g n a n (a - g f a g - f) a f an

an n g n a n (a - f f a g - g). ERP -
f d g n d a P2 n n a g a f a
f f d g a , a n d 250 a f n ,
a f f g n an f n g n
a f g . In add n , n n a b f M a d
f g n f a a f a d n d g n -
n d a g a g n f a a f a
a n d n n g n .
A d a n g n a a b n a -
n d n an MRI d b a d g an , M f and N n
(2009), a n d f f n d b a a n
f n . d a a - a n n a f a g
n n b f f d f n a d d f n a
n a f a f b n an f f an
g d f a f n d a a g n b n ,
f n g n . a d f a a f a n
n d g n f g g (f d real
auditory motion), a f a n a n d a g g n
n a n a d f d n a d d f n (n d g “ n
n ” and a g a n n f a d f n),
f a n d a g “ ” f “ d n . ” A b a f a
a f n d n d d an a a g d f n a
b a a n f . A n f a ,
a g , n f n (n d g n a a d
f g a d d f n) n n d a a n
f g a f a n an n (M +
W 5+), n - and a f n ,
d n d - n n d g n f a a n .
n d a a n n a n g n a f f n -
g f a d n d a n a f a , f f a n n
and g d f a f n g f - n f -
g n f g n .

Theoretical accounts and models for immediate effect and aftereffect

Bayesian

n n g n f a n f n d a f f f
da , da a g b a a a d -
n a . F f a g , n d g a n n a modality
appropriateness and precision hypothesis (& a f n ,
1980). In d a a a n f f , a da -
a b f a a a , and g d f n
f f a b a d a d a n (H a d
& n , 1966). In f a n f f , n n -
f a f , g d f da f f n d f n a g
f a f a n , and f d a f a a
a n f f f d a d n d . A d f n
a an d a a n g f a n
Bayesian a . d a f a a d f and a a
a f b n d n an a a b g g a

fa an a n n fa f an n da -
a f g f (Aa & Bff, 2004 ; Bff & Aa ,
2006; a , & A afa, 2007).

fa d a d d d a n fa n
Ba an n f n . g n fa, nd f and g
Ba an a f a a an n f n b a d n
a f , d and f f . d f f -
n n f n n n f n n f n b fa n,
f f a f f a f a n n
n f n n (Aa & Bff, 2004 ; B g a, J b &
A n, 2003; Bff & Aa , 2006; E n & B a , 2002;
a a ., 2007; a & B f , 2010; a .,
2010; n & K d n, 2005). a a a n a ,
Aa and Bff (2004) d n fa d a n f a g
f f n a f - a n g fa n. n a
a a n g d, nd na and a f nd,
b f f b f f d a , nd a f -
n. K f d g a . (2007) nd d d f a g
and a b f f d a f n f f f n f
g na f a n (n f n f
b nd g) and n n a a n f
f . a a g d a a a n f a
f f n d n , g - g n n
b f f d n a and f n f n
(K f d g a ., 2007).

Ba an n f n n a a n f a a b n
a nd f a ad f ad n (B ,
M f d , Van O a & M n , 2005; Van an ,
B , M n & Van O a , 2009). n a d a -
a f a a ag n d n 20 f a afa n
and b f f a f n and f f a a a g ,
b a n and a f a f , f a
n n f and ag n d nd n . nd a
a f b - b - f d ” (C f n , Van an ,
M n & Van O a , 2002), n f b f f b n
f a a a f a f d a n n ,
and a f f a n n a g g f d f

n n . f f a n b a d a a a
ag n n a a f : a , a f an a f a f n
ag n d f a n 1(n a , (Ogl) Ja

L a n, 1993; M h , M f a , M , f a n, M d f ,
C a f & M , 2007; R & D , 2002; f d f &
F , 2005). B n f a n f d a g g a
n f a f g a b b a d n f b a n
d g . d d a f n b f a n
and n a n a a n f q and
a f

f a f a b f a n b a g , f n -
n d n f f d . A n a a
a f a a a a r a and a
n f d a n g a n f n a d a -
a n d a a a f f a r a a f
f n n n d f a n f a d a a n -
n r a a a f .

Computational approaches on temporal ventriloquism: Bayes and low-level neural models

B a n a f a a a b n a d d n d f and
f a n f q (B f a ., 2009; H f f -O B n
& A a , 2011; L a ., 2009; a ., 2010).
H f g , d f n f n d g n a a n f -
q , a d f f a a a n a (d -
r a n q d f f a n f a f n) a
f a n f d a a d a -
n , a g f a a a n d a a
a b f a n f a n a n .
M a a , a a , d a n d K a a a (2006) -
d a B a n a b f a n a f d f g g -
n f g a d g g d a f a f d f b a
n a d b n d g a d a a n a n
(M a a a ., 2006). B a n g g a d a a n b
g f n d , n n f d
“B a n a b f a n” a a f g b n d g a d a -
n (a a , M a a , I a n & K a a a , 2012). I a
f n d , a and A a a (2009, 2011) f d a
n g B a n d a n f f a n f -
q a f . A f d g d b g a d a -
a n and “B a n a b f a n” a n f g a d d a
B a n a d a a n , f f a a d a a n
d n n and a f a a d a a n f f
f b b . d n f f a f a b - f a a d a
f f g a d a a n and a
a f f d b n .
A n f n f g a f a n d f and g n f a
and a a n a n n d f g f a
f a b f a n a b n f a R a a . (2011) f
d a g a n d G a a . (2012) f f - a
g . f a n , f a g f a d a -
f n f d b a a f a f a -
a b f n f n n d d f n d a .
f a n g f a f a d a a n d . f b
R a a ., f a d a f d
g a n n f n n d d a , g n a f a -
a a f a n f n n b q n
a a f a d a . G a a a d d a a
d f n a f a a a d a a n d a d d -
b a b a g g n g d a - n
n f n . I a b d a f f a a n n d f

Neural mechanisms in spatial ventriloquism

a n a n d a g r a f , a , 5 n
n f a identical a n d a a a g r a f
n b n f q a 5 ? q n
f a a n g g a b a f f a a n f -
q f a g n n f f f a b -
f d f n b a . sensory a n a
a n f f a d a a f b n d a a f
g f g a n d a n f d n g f a -
n f a a b n a a n (B f n ,
1999; C n , R d a , q , D a & D n , 2002;
K a a & I a a , 2002; b g , n & d
G d f , 2004; n a ., 2004 b ; n & d
G d f , 2003). decisional account g g a n
f f a a a a n d n and a
b a f a f a n g r a f f n n f f -
n , d r a b a , f g n b a (A a & B f ,
2004; M f & g f , 2001; a n f a , n &
f a , 2007; f g f a ., 2003).
ERP n q , g n f a f -
n , a f d a f f a a
n f q f f . a n g a -
(MMN), n d a d n a
d a n n d f a f f g n a q n and a d
b a g f n d n d , a d b d a a
f a n (G a f , 2007; N a a n n , B a a n n ,
R n n & A , 2007). I n n a a n a n
a n d a n a n MMN. f f a f ,
a a f a a a f MMN a n a n illusive
n a a n a n d n f q a
a a a g n f n a f n -
n n . f a d a n d d f f d a MMN
f d n n f n q d f a a
a a n d n f n f q (C n
a ., 2002), f f a f f d a a n MMN a n
a a n a n f b (a a r a f)
n d n d a n f n a (b g &
n , 2009; b g a ., 2004).
B r a a . (2007) b n d ERP f n f a d
n n a g n f r a n g g (MRI) d n -
f a a a f a g f g b a a n
q d f f a b d f a n a n
n . ERP f d g

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- B., P., W., J., d G., B., & B., J. (2000). n ... f ... d ... n ... d ... f ... a *Perception & Psychophysics*, 62, 321–332.
- B., P., W., J., G., G., & d G., B. (1994). *Exploring the relation between McGurk interference and ventriloquism. f ... h ... C ... n ... l ...*, 559–562.
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- B., J., B., D., B., G., C., & B., J. (2005). n ... f ... a ... f ... a ... a ... and ... a *Brain*, 12, 1571–1583.
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- B., J. P., & E., M. O. (2007). g ... f ... d ... a ... f ... -a ... ng ... f ... n *Neuroreport*, 1, 1157–1161.
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