

Principles of Psychology and Neuroscience, First
Edition

Randall C. O'Reilly

Principles of Psychology and Neuroscience

(The Three C's)

First Edition

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<https://github.com/PsychNeuro/ed1>

To my family.

Preface

This is an in-progress experiment – feedback is more than welcome.

Chapter 1: Introduction

Introductory Psychology textbooks typically provide a rather fragmented, fact-laden view of the field, relying on colorful graphics, exciting news stories, and personal anecdotes to generate interest in the material. This book represents a radical departure from that approach. Instead, the goal here is to provide a simple, succinct, principled account of the human mental world and how it emerges from our brains, that is coherent across the scope of phenomena covered in typical Intro Psych texts.

The overall portrait painted of you looks something like this (caution: it is not overly flattering, and you might even think this song is not about you, but go ahead and be vain – it is): You are obsessed with controlling your environment to satisfy a range of core desires and to mitigate strong fears. You are unlikely to be swayed by other people's advice, but have no problem dishing it out. A challenge to your social standing or any other form of disrespect (the *diss*) is one of the worst offenses. You are willing to spin all manner of stories to maintain your sense of order in the world, *especially* when that sense is strongly challenged, often to the point of absurdity in the eyes of others.

You crave simple ways of understanding the world, to the point of massively oversimplifying the true complexities and ambiguities, preferring to think in terms of concrete anecdotes instead of broad abstractions, logical arguments, or, especially, statistics. You think you know how most stuff you use everyday works (bikes, cars, toilets..), but studies show that you are actually remarkably clueless – how exactly does that chain on a bike work? Perhaps most glaringly, you can't help but think in terms of stereotypes, and inevitably focus on information that is consistent with your existing views, while ignoring all those nagging hints that all may not be as simple as you might like.

You only care about things that are new and unexpected, and are constantly comparing and evaluating yourself and others with a keen eye for who is doing better or worse along any number of important dimensions (wealth, beauty, smarts, athletic ability, popularity – you name it!) You are hypersensitive to who might be cheating or gaming the system, but are perhaps not so aware of unfair advantages you might have. More generally, you tend to think of yourself as being “your own person” and strongly underestimate how strong of an influence other people actually have over you. If you're honest with yourself, you'll admit that you spend way too much time thinking about what other people think of you – without recognizing that everyone else is doing the same thing, so that in fact the answer is a somewhat disappointing: “not much” (unless of course you do something embarrassing or strange or stupid, but even then, your memory of those events will typically far outlast those of others).

In other words, you are a *survivor*. You are a tough cookie. Your ancestors survived unbelievable hardships to get you here, to your relatively plush college-educated world. You are amazingly efficient. All those crazy details you don't know about the world are largely irrelevant anyway. Seriously, does it really matter that you don't know how the engine or transmission in your car works?

You can drive, and get to where you need to go – and that is what really matters. Your brain is exquisitely tuned into what really matters, and despite over 60 years of attempts to recreate the magic of your brain in a computer, nothing has come even close (despite all the recent media hype to the contrary).

And yet, despite all your toughness and amazing abilities, you are very likely to have at least some level of significant mental dysfunction. You are more likely than not to suffer from depression, anxiety disorders (and often both of those together), drug dependence, etc. Unfortunately, the promise of a magic pill to cure these afflictions has turned out to be yet another disappointment. In fact, regular old “talking to another human being about your problems” (i.e., therapy, which is actually somewhat more involved and structured than that) is likely to be more effective than medication for most people.

The Three C's

Surprisingly, we can make sense of all the above (and more!) using only three core principles:

Compression

Each neuron in the most important part of your brain (the *neocortex*) is wired for simplification, and the collective effect of the massive waves of electrical activity surging through your brain every millisecond is to compress, reduce, and simplify information. Each neuron receives input signals from roughly 10,000 or more other neurons, but guess how much it can then say about that flood of information coming in? Almost nothing. First of all, it only has *one* output signal, the *spike*, which is an all-or-nothing affair. Furthermore, a typical neocortical pyramidal neuron will fire at most around 100 spikes in a second. And a second is a relatively long time in the inner loops of the brain – there is evidence that 1/10th of a second represents a kind of fundamental time-frame for information processing, so those 100 spikes reduce down to just 10 spikes within that critical window. And most neurons are firing far less rapidly than that. It's like when you tell your friend all your deepest thoughts, and they just say “huh”. Neurons are the strong, silent type most of the time. But still waters run deep: when neurons *do* get excited about something, it is likely to be *important*, and most of what they are doing is *shielding you from constant TMI* (too-much-information – but you knew that already, so, kind of a meta thing we got going there...)

The raw scene coming into your eyeballs is truly gory: all jumbles of light, motion and color. When you were a tiny baby, you were overwhelmed by this “blooming buzzing confusion”, but now your neural networks have learned and developed to the point where you don't (can't!) even see that raw sensation anymore (unless of course you partake of various hallucinogenic substances, but even then, the level of disorder experienced is trifling compared to the pure chaos of the raw, unfiltered tidal wave of sensation coming in). We get small,

fascinating hints of the magic power of our perceptual systems through illusions, and the occasional “viral gold / blue / brown dress” controversy, where people strongly see or hear very different things from the very same stimulus. But overall, we really have absolutely no idea how much undercover cleanup work is going on inside our brains. If anyone was truly aware of the level of conspiracy operating in there, it would be scandalous. But, somehow, amazingly, we largely all end up converging on the same stable, boring illusions of simplicity. A table. A chair. Some french fries. People walking down the street. Cars driving by. Nothing strange going on here.

We would be utterly nonfunctional without this compression. For the same reason that those hallucinogenic drugs render people nonfunctional. If you want to do something useful with your time, you need to be able to make everything else in the world boring and irrelevant, so you can focus on *what matters*. If you’re reading a book, or your tiny screen, it simply wouldn’t work if every time you moved your eyes, the whole world was seen afresh, requiring you to reorient and rediscover what you were just reading and what you need to read next. Interestingly, this capacity for perceiving a stable, boring world seems to depend critically on a very active underlying process of *prediction* – your brain is stitching everything together in a seamless whole by filling in the gaps with what you *expect* or *predict* to see. You can easily see this, and relive some of your earliest experiences, by simply closing one eye, and then gently pushing on the bottom of the eyelid of your other, open eye. Suddenly, the world is a moving jumbly mess again! (Seriously, try it!)

Your brain’s penchant for simplification (compression) does not stop with perception. Your highest levels of thought are similarly dominated by the same quest to render everything simple and predictable. Instead of recognizing the incredible high-dimensional diversity of our fellow beings, we inevitably reduce everyone to stereotypes. Even members of negatively stereotyped groups are caught in the evil maw of this process, exhibiting similar levels of stereotype-driven biases as everyone else. The ultimate expression of this compression process is the *anosognosia of everyday life* (aka the Dunning-Kruger effect; <https://opinionator.blogs.nytimes.com/2010/06/20/the-anosognosics-dilemma-1/>) – the lack of knowledge about our utter lack of knowledge. People can be remarkably unaware about what they don’t know, and sometimes, this leads to funny situations. But, amazingly, most of the time, *it causes no obvious problems whatsoever*. We just keep getting on with our lives. And, as with perception, if we didn’t, we’d never get anything done, because there is such a huge amount of stuff we routinely, safely ignore, that it would take many many lifetimes to process and understand it all.

Contrast

The next principle explains why we seem so fixated on comparing ourselves with others. Not just any others, but those certain people *who really get to you*. In that inexplicable, frustrating way. Why do I always have to be so jealous of those

people? Can't I convince myself that the "grass is always greener?" Nope. As with compression, your brain is wired at the lowest level for magnifying contrasts, in this case via a special class of neurons called *inhibitory interneurons*, coupled with other important properties of all neurons that we'll cover in Chapter 2. The net effect is that your brain only sees things *relatively* (yep, we can have our own, special, relativity law in Psychology too – actually it is pretty general). A classic example of this is when you come in from the bright sunny outdoors into a dimly-lit room. The difference in raw light energy coming into your eyeballs in these two situations is enormous, but, after a brief period of adaptation, you're seeing things in the dim room that differ by a few photons here or there, whereas outside those few photons would be a minuscule drop in the bucket. In other words, our neurons *normalize* away the raw strength of whatever signal is coming into them, and remain sensitive to the *relative differences* compared to that overall signal. Those inhibitory neurons play the critical role of mathematically *dividing away* the raw signal strength, leaving the principal pyramidal neurons "in the zone" for responding to relative differences.

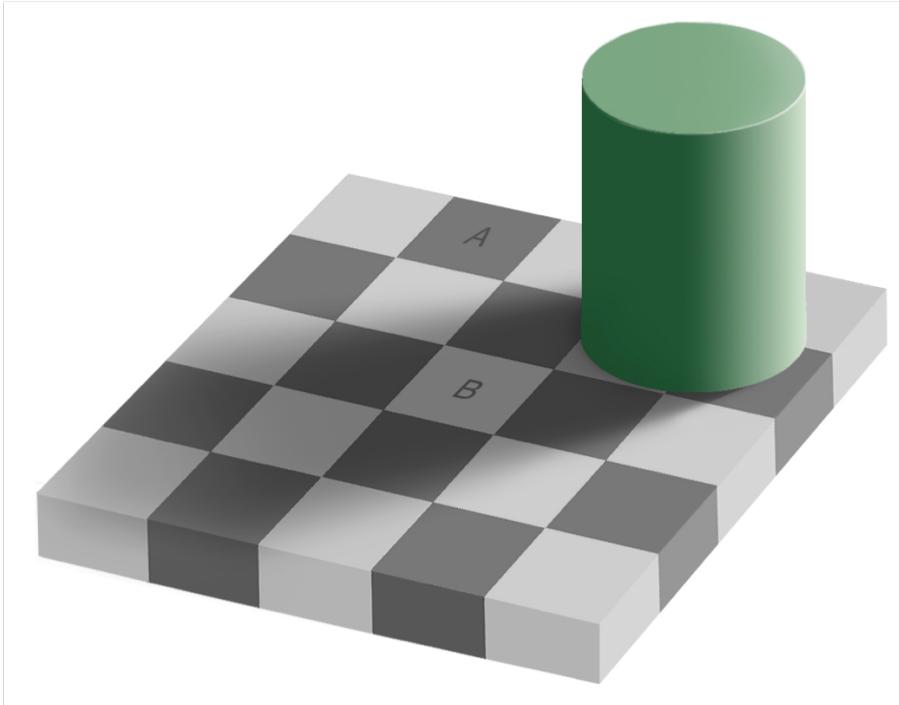


Figure 1: Fig 1-1: Illustration of the power of contrast in perception. Do you think the physical image-level color of square A is the same or different from that of B? Unbelievably, they are identical!

As with compression, perception provides some of the clearest windows into this phenomenon, for example Figure 1-1, showing the remarkable effects of

contrast (and global scene understanding) on perception of color and brightness.

But contrast, like compression, is not restricted to the perceptual domain. It affects every level of thought, contributing to that insidious obsession with your relative standing among your peers. For example, studies routinely show that the absolute amount of money that people make is largely unrelated to various measures of their happiness – instead, what matters is their perceived level of income *relative to their peers*.

Contrast operates over time as well, in several important ways. First, at the perceptual level, we are highly sensitive to the rate of change over time of stimuli. The classic example here is the slow approach to boil being unnoticed by a hapless frog until it is too late (this is not exactly true – you can't get all the way to boiling, but it is very likely true to at least some extent). Similarly, a cottage industry of amazing demonstrations of our inability to detect slow changes in visual scenes sprung up a few years ago: YouTube Link to Dan Simons Video: <https://www.youtube.com/watch?v=1nL5ulsWMYc>. Once you become aware (upon repeated viewing or instruction) of the nature of these changes, it is truly astounding to realize how much you overlooked them the first time(s). If you rapidly flip between the start and end frames of these slow-moving videos, the changes pop immediately into view. Again, we see the *delta*, not the absolute value of things.

Nowhere is this more poignant, and pressing, than deep inside the *dopamine* system in the middle of your brain. As you already know (and would be annoyed to have me repeat, but I'm going to do it anyway, to prove the pertinent point), dopamine is widely believed to be the “pleasure drug” in your brain. It is associated with drugs of addiction, and actually most other major mental disorders in one way or another. However, this popular description of dopamine leaves out one of the most important points: dopamine is *not* about *raw* pleasure, but rather, about the *difference* between what you experience and what you *expected* to experience. Specifically, if you get exactly what you expected, your dopamine goes “meh”. This soul-crushing response to your greatest accomplishments is exactly what critics do to performers, and indeed the dopamine system is best understood as being the *central critic* of your brain. Far from a center of epicurian delights, it is a hard-nosed bully that is never satisfied. And that dissatisfaction is what has driven us ever upward in all manner of exploits – many of them good, but many of them not so good.

Greed is really a byproduct of your dopamine system. Seriously, why in the world can't someone who already has *millions of dollars* just be happy with that, and give the rest away or do something else useful with it (and their all-too-brief lives). Because dopamine adapts quickly to that million-dollar feeling, and it keeps giving you back that critical “meh” response. You need more than that. You *deserve* more than that... It really is tough living with such an asshole critic in your head all the time. But then again, we really do owe every step of “progress”, within our individual lives and as a society and a species, to that nasty little critic driving us ever upward and onward.

Finally, another obvious manifestation of the contrast principle is our collective obsession with the *news*. Especially with the advent of the 24hr news cycle and the constant updating of news information via electronic, online media, we are now living in a quickly-moving bubble of news that sweeps things up in its path and spits them out quicker than... yesterday's news. Or yesterhour's news. If you don't check in quickly enough, you'll miss huge swaths of news that everyone would have definitely been aware of before. Everyone worries about this kind of thing, but really it is just what our brains are wired to do. Every conscious moment of our lives is driven by a thirst for knowing what has changed, what is different – anything that remains constant will quickly drift out of your mind, like that delicious aroma of dinner that I can no longer access, or, thankfully, that feeling of my butt sitting on this chair that I was thoroughly *so over with* until I just wrote that sentence..

Control

Last but certainly not least, is our obsession with control. Some of you may be thinking that you're not a control freak like those *other people*, but actually, every one of us is a crazy control freak at some level – it just differs in terms of what matters to us. Anyone want to have some stranger come pick you up and take you around to work with them all day? Or just invade your personal space? How would you feel if someone just started selling all your stuff on craigslist? Or how about those people who go door-to-door (or stop you on the street) and try to convince you to believe in some particular brand of religion? Or just your roommate who keeps nagging you about the dishes, or being to loud, etc. Yeah, there's definitely *something* for *everyone*, where it matters. And usually, if you have two or more people living together, you quickly become aware of all that stuff that you didn't realize really matters to you. A lot.

Starting again in the brain, virtually every neuron in the brain is serving the master of control at one level or another. At the most basic level, control is about *motor control*, and a great example of the dedication of the brain to this particular function comes from a lowly sea squirt that starts off life as a mobile tadpole, and flits around in the ocean for a bit, looking for a good place to settle down. As soon as it finds its special place on the reef, it promptly eats its own brain! Because, the whole point of the brain in the first place, evolutionarily speaking, is to process sensory inputs *in the service of producing useful motor outputs to improve survival and the overall quality of life*. There's a reason nobody thinks highly of layabouts and 30-year-old's living in their parent's basement: progress requires action, and our brains are wired for action. In the brains of most species, there are big chunks devoted to the compression and contrast processing of sensory inputs, and the rest is devoted to using that information to figure out what kinds of opportunities and threats are out there in the world, and how to best optimize chances of survival within the repertoire of available motor actions. Not much space left over for cultivating expertise in civil war battles, or fantasy role-playing games, or whatever other weird,

seemingly non-functional things people spend their time doing.

The human brain takes this obsession with motor control to the next level, by building an internal fortress / castle of the *self*. We're not quite sure to what extent any other beast even has a similar kind of thing inside their own mental worlds. The self is a model, a construct, built up over years, that helps us predict (again) how we are going to behave, and what we seem to really want (and not want). By having such a thing inside our own brains, we can use it to more accurately anticipate what kinds of motor actions are really going to get us what we want. This is especially important when dealing with other people, who are, compared to your average rock or tree, very complicated and unpredictable. I'm not saying you're a manipulative little jerk. I'm saying *everyone* is a manipulative little jerk, deep down. It is, again, just a logical extension of what brains are supposed to be doing. If they aren't good for maximizing pleasure and minimizing harm, then we might as well all just eat them for dinner!

This *self model* lying at the heart of our control system is like our secret nuclear power reactor inside our brains. It is the "nerve center" of our being. It does *not* take existential threats kindly. Anything that appears to threaten our internal sense of identity and control gets raised to the red alert level. This is why you can't just "mansplain" something to someone else, and expect them to instantly see the error of their ways, and instantly become a new, better self. We have a lot of investment in that *old self*, and it does not look kindly on being deposed from its despotic rule over its own internal kingdom.

Although the self is a despot at heart, it is also remarkably sensitive to external, social forces, creating one of the most fundamental and puzzling paradoxes of the human condition: We care deeply about what other people think of us, and are actually remarkably malleable in adapting our behavior under the influence of others. There are many demonstrations of the power of the social force, from the evil of Nazi Germany and controversial attempts to recreate those forces in the lab, to the seemingly more benign and amusing phenomenon of hypnosis. Biologically and ecologically, our very survival is utterly dependent on our ability to work together socially, and social motivations are undoubtedly wired directly into the depths of our brains, providing these "hijack" pathways past the watchful eye of the self-model.

And therein lies the likely explanation for this paradox: these social forces can only act when delivered in ways that the self either does not recognize as threatening, or even endorses. The minute you are aware someone is trying to convince you of something, is the minute that it fails. But when a social virus is neatly packaged in a nice sugar coating, often in terms of reinforcing a sense of belonging with an identified *in-group*, then it can easily slip past the guards. These kinds of in-group / out-group (tribalism) dynamics are the strongest of social forces and underlie all the greatest evils of humanity. And probably many of our greatest triumphs too.

Developmentally, the self emerges around age two, heralded by the onset of

tantrums. Tantrums are the inevitable consequence of an emerging desire for control, coupled with an almost complete lack of *actual* control. This is really the defining battle of life, and it never really ends: the best you can hope for is some kind of truce as expressed in the Serenity Prayer of Reinhold Niebuhr: “God, grant me the serenity to accept the things I cannot change, Courage to change the things I can, And wisdom to know the difference.”

The Breakdown of Control

Unfortunately, achieving *serenity now* is very difficult. And all those challenges to the self can end up leading to a bout of depression, often coupled with anxiety or other unpleasant mental states. Although widely characterized in terms of *anhedonia* or the inability to experience pleasure, current research supports the idea that the core disorder of depression is really about *control*, or the perceived lack thereof. When your self model is sufficiently challenged, it basically gives up on a lot of goals, and unfortunately, achieving those goals is a primary source of pleasure and satisfaction in life. So, yes, anhedonia is a consequence of depression, but the core of it is more about the inability to motivate yourself to get out of bed and do all those now-meaningless things that you used to find meaningful.

Consistent with this central role for control, one of the most promising components of modern therapy for treating depression is *behavioral activation*, which is essentially an attempt to reboot your core self-motivation control system. Indeed a major study found behavioral activation to be the most important element among a group of therapies, and as effective as medication (Dimidjian et al, 2006). And when you recognize the central role for control in depression, it is then less surprising that medications are relatively ineffective: for the vast majority of people, the problem is *not* about some kind of low-level imbalance in their brain chemistry: it is about their core mental power plant running out of steam. And it just takes hard mental work, aided by effective therapeutic treatments, to reboot your own sense of mental self-control and efficacy.

For the smaller proportion of people who clearly do have a biologically-based mental disorder, it is still the case that the brain areas most centrally involved in self-control are the ones that are most likely to be affected. Schizophrenia and OCD for example involve the frontal cortex, basal ganglia, and dopamine systems of the brain, which are the main players in developing and sustaining our internal self control system. Thus, understanding how different parts of the brain function to support this critical self-model system is a major goal of current research in Psychology and Neuroscience, and this book is designed to get you started on a journey toward understanding this cutting-edge work.

Other Principles and Perspectives

There are many candidates for “the fourth C”, and different names could have been chosen to refer to the above “three C’s” (e.g., reduction, relativity, and... respect?), but being a slave to the simplifying force of *Compression*, it is useful

to try to see as much as possible through the lens of these three principles. Furthermore, as briefly introduced above, these principles can be tied directly into the most fundamental properties of the nervous system, and thus provide a critical *bridging function* between Neuroscience and Psychology. Nevertheless, it is important to always remain aware of all the compressing taking place, and to acknowledge that this radical attempt at synthesis may strike many practicing scientists as overly simplistic or downright wrong-headed. However, my hope is that the benefits outweigh the costs overall, without attempting to overly minimize those costs.

Where do we go from here?

This question can be asked at two levels: the short-term question of where this book is headed, and the longer-term question of where our species is headed!? Although it may seem like our current cultural and political environment reflects an extreme magnification of many of the negative aspects of human mental function as described above, another perspective is that these truly are perennial battles and challenges that we have struggled with since the dawn of human history, and that they are borne of fundamental properties of the human brain that also have many positive aspects. Like everything it seems, double-edged swords abound. And the core premise, and promise, of science is that by understanding something deeply, we are better positioned to make the best of it. This contrasts with the idea that by somehow reifying “bad” features of the human brain, we are therefore justifying the bad ends they produce. Clearly that is not the aim here, and my personal optimism leads me to believe that this endeavor will be a net benefit in the end (or at worst, simply irrelevant).

With those big picture questions out of the way, we can turn to the plot for the rest of this adventure story through the human brain. Unlike a good mystery story, we’re going to ruin the whole thing right up front, in the hopes of achieving a better understanding and mental roadmap in the bargain.

Chapter 2 will cover the nuts and bolts of the brain, but always connected directly to the bigger picture via the three-C’s principles and their applications. We’ll see in detail how each neuron functions as such an amazing “information compactor”, compressing those 1000’s of signals into its single spiky output. We’ll then take an amazing “connected” voyage through the pathways of the neocortex, seeing how the great chain of neurons locked in their long-lasting embraces create channels where information flows in different ways. We’ll wrestle with the central question of whether brain areas are truly “specialized” for different functions or not, and whether there is any “there” there, as in, “where *is* that memory anyway?”

Chapter 3..

etc.

Neuroscience

NOTE: not updated – just a placeholder

One major reason the brain can be so plastic and learn to do so many different things, is that it is made up of a highly-sculptable form of *silly putty*: billions of individual neurons that are densely interconnected with each other, and capable of shaping what they do by changing these patterns of interconnections. The brain is like a massive LEGO set, where each of the individual pieces is quite simple (like a single LEGO piece), and all the power comes from the nearly infinite ways that these simple pieces can be recombined to do different things.

So the good news for you the student is, the neuron is fundamentally *simple*. Lots of people will try to tell you otherwise, but as you'll see as you go through this book, *simple neurons can account for much of what we know about how the brain functions*. So, even though they have a lot of moving parts and you can spend an entire career learning about even just one tiny part of a neuron, we strongly believe that all this complexity is in the service of a very simple overall function.

What is that function? Fundamentally, it is about **detection**. Neurons receive thousands of different input signals from other neurons, looking for specific patterns that are "meaningful" to them. A very simple analogy is with a smoke detector, which samples the air and looks for telltale traces of smoke. When these exceed a specified threshold limit, the alarm goes off. Similarly, the neuron has a **threshold** and only sends an "alarm" signal to other neurons when it detects something significant enough to cross this threshold. The alarm is called an **action potential** or **spike** and it is the fundamental unit of communication between neurons.

Acknowledgments

Thanks to the current beta-testers for reading!

Glossary

About the Authors

Randall C. O'Reilly is Professor of Psychology and Neuroscience at the University of Colorado Boulder.

References